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TOWARDS THE INCLUSION OF GREENHOUSE GAS FLUXES IN THE CARBON FOOTPRINT OF VEGETATED WSUD

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ABSTRACT: *Rapid global urbanization has resulted in more impervious surfaces within urban areas, which has caused additional pollutant loads on stormwater control systems. Water sensitive urban design (WSUD) systems have been developed to reduce the environmental impact on urban ecosystems by reducing the pollutant loads generated in and passed out of the catchment. Stormwater runoff quality and quantity have been well studied in urban catchments, while the ecosystem services and disservices of WSUD have received less attention. During the last decade, the impact of climate change has received a great deal of attention by the general public and decision makers. The carbon footprint is a useful indicator of the global warming potential (GWP) for urban infrastructure. Using a whole of life cycle thinking approach for the carbon footprint, four separate phases are identified, namely material production, construction/installation, operation and maintenance, and end-of-life phases. In spite of the attention on carbon embodied in these phases, the greenhouse gas (GHG) emissions have not been adequately recognized as a part of the carbon footprint of these systems. This paper identifies the importance of the GHG fluxes from vegetated WSUD basins and presents a conceptual approach to their inclusion in the life cycle carbon footprint. It has been shown that the estimation of carbon footprint just within the life cycle phases underestimate the total carbon footprint by ignoring the GHG fluxes. Despite the scarcity of available data on vegetated WSUD basins, the direct GHG fluxes over the life span of the vegetated stormwater basins can contribute to a large amount of carbon to the environment.*

KEYWORDS: Green stormwater infrastructure, Water sensitive urban design, Carbon footprint, Life cycle assessment, Greenhouse gas fluxes.

1 INTRODUCTION

Our societies are facing two major interconnected environmental issues of urbanization and climate change [1]. Urban populations around the world are increasing rapidly. The increase in the population of dense urban areas is changing the social and ecosystem geography of all urban cities. The removal of vegetation and development of more impervious surface areas as a consequence of urbanization has changed the characteristics of the urban runoff. Hence, more volume of stormwater runoff and peak flow rates, causing higher pollutant loads on stormwater control systems [2].

Recognition of stormwater as a source point of pollutants initiated the creation of water sensitive urban design (WSUD) systems. These systems can be defined as "a philosophical approach to urban planning and design that aims to minimise the hydrological impacts of urban development on the surrounding environment" [3]. WSUD is an internationally recognized approach to develop a sustainable urban water cycle by employing low impact technologies to increase quality and decrease quantity of stormwater. WSUD devices include various systems such as bioretention basins, green roofs, rain gardens, buffer strips, swales, sedimentation basins, sand filters, porous paving etc.

Traditionally, studies of these systems have been mostly focused on the downstream effects such as stormwater volume reduction, erosion control, and water quality improvement. While the runoff quantity and quality benefits of WSUD systems have been the main focus of attention, the provision of ecosystem services and disservices, the environmental impact assessment and their contribution to greenhouse gas (GHG) fluxes, are emerging research interests.

The existence of GHGs such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) and water vapor in the atmosphere causes the cyclic trapping of heat in the Earth's atmosphere and prevents rapid dropping of the average temperature of the Earth's surface. The global emissions of CO_2, $CH_{4,}$ and N_2O have increased by 70% as a result of human activities since the pre-industrial era (1970). Due to the dramatic rise in GHG emissions, scientists predict that this trend will lead to consequential advanced warming [4,5].

The process of CO_2 fluxes is comprised of anaerobic and aerobic respiration in belowground (soil) and aboveground respiration [6]. CH_4 and N_2O both are mostly produced under anaerobic conditions. CH_4 fluxes are release due to the methanotrophic process in soil [7]. N_2O fluxes are released by denitrification and nitrification processes under anaerobic and aerobic conditions respectively [8].

The fluxes of GHGs in various natural ecosystems such as natural wetlands, riparian marshes, constructed wetlands, wastewater treatment plants, stabilization ponds and freshwater marshes have been well studied [9–11]. It has been shown that various wetlands with different site-specifications are globally recognized as sinks for CO_2, but are sources of CH_4 and N_2O [12,13]. However, little research has been presented on these fluxes in WSUD basins.

As a result of the recent increase in interest on climate change issues, the concept of "carbon footprint" was introduced to provide a better understanding of the contribution of a system or process to climate change. The carbon footprint can be expressed as the total amount of GHG emissions which are emitted from a process or product [14,15]. It can be quantified using indicators such as the global warming potential (GWP) to quantify the contribution of GHGs to global warming and climate change [16–18]. The carbon footprint is the result of applying a whole of life cycle assessment (LCA) methodology to quantify the GWP indicator [19,20].

The LCA is an environmental management tool used to quantify the environmental impacts of products through different stages of their life [21,22]. The LCA framework is a standardized and reliable tool based on the International Standards Organization, the ISO 14040 series, which is categorized into four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation of the results [23–25]. According to ISO 14040 and ISO 14044 standards, a carbon footprint study follows the four phases of LCA. Then all assumptions, limitations, and processes of an LCA approach influence the resulting carbon footprint [26].

The four phases in the LCA include the following:

- Material production;
- Construction/installation;
- Operation and maintenance; and
- End-of-life.

The carbon footprint associated with the different life cycle stages of WSUD devices have been well documented in the published literature [27]. However, the direct GHG fluxes from these stormwater basins have received less attention. Many research studies and the popular media often focus on CO_2 as a well-known anthropogenic GHG, but, CH_4 and N_2O have 25 and 298 times more global warming potential than CO_2, respectively [28].

In this study, the direct GHG fluxes from vegetated WSUD basins have been reviewed and analyzed for inclusion within the overall carbon footprint of these systems. The assessment of direct and indirect emissions from stormwater infrastructure can provide designers and policymakers with an insight into the whole of life cycle of these systems, including the direct GHG fluxes and the carbon embodied within the life cycle phases.

2 METHOD

Along with the four life cycle phases of the traditional carbon footprint analysis, this study includes GHG fluxes as an additional component of the carbon footprint. The inclusion of GHG fluxes in the carbon footprint has been conceptualized as the total amount of three major GHGs (CO_2, CH_4, and N_2O) fluxes from these vegetated stormwater basins (Fig. 1). The literature pool of this study is selected as a part of a systematic search which has been performed by the author of this work. All the vegetated based WSUD systems namely: bioretention basins; swales; stormwater ponds; raingardens and green roofs had been searched in four databases (Science Direct, Scopus, ProQuest and ISI Web of Knowledge). The findings of the search were grouped into further appropriate categories. This study focuses on the direct GHG fluxes from the vegetated WSUD to the atmosphere.

A comparison of the published research requires the use of a consistent functional unit and life span for all of the devices. However, the data reported in the published literature is presented in a variety of different units. The analysis presented in this study has included the conversion of all of the available data (with varying unit values) into a common unit of kilograms of CO_2 equivalent per square meter of surface area of the WSUD device (kg CO_2 eq. m^{-2}) – thus making study comparisons a relatively easy and clear task.

The GWP factors of 25 and 298 were applied to convert relevant non-carbon dioxide gases (CH_4 and N_2O respectively) to an equivalent mass of CO_2. In addition, the multiplication factors of 3.66, 1.336 and 1.57 were respectively applied to CO_2-C, CH_4-C or N_2O-N to convert them to CO_2, CH_4, and N_2O [29]. Finally, the results of the review analyses have been compared with the carbon footprint values reported by Kirk, 2006. In their study, a set of stormwater management technologies such as bioretention basin, wet pond and gravel wetlands were designed for an annual treatment of stormwater runoff.

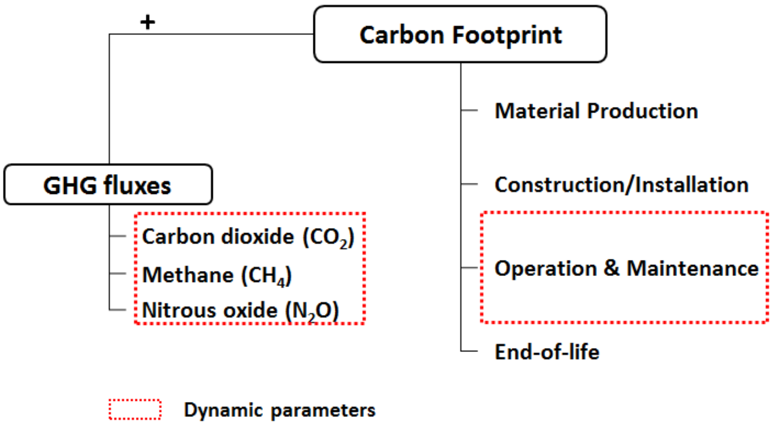

Figure 1. The phases and sub-phases in the whole life cycle carbon footprint of vegetated WSUDs.

3 RESULTS

In determining the carbon footprint of vegetated WSUD devices, the system boundaries must be defined for all of the processes within the life cycle analysis. These system boundaries must clearly describe the physical, spatial and temporal boundaries and the inputs and outputs of the system. The international standard of EN 15804: 2012, (for building material), has defined three levels of system boundaries:

- *Cradle to gate*: This covers the material production phase, including any upstream processes from the raw material supply, material manufacturing, and transportation to the construction site.

- *Cradle to gate with option*: This covers the material production phase as described above, but can also include either the construction or maintenance activities.
- *Cradle to grave*: This covers all stages of the life cycle including the production, construction, operation and maintenance and end-of-life phases.

The cradle to gate and cradle to gate with option are the most used boundaries which have been employed in the published literature. However, the inclusion of the construction activities and operation and maintenance, varies between the studies [30].

The carbon footprint contribution of the first three phases of material production, construction/installation, and end-of-life phases can be recognized as static parameters. On the other hand, the operation and maintenance phase covers the total life time of the stormwater device and is a time-dependent or dynamic parameter (Fig. 1). In this regard, the GHG fluxes from stormwater basins are also dynamic parameters which must be accounted for in the total carbon footprint analysis of the vegetated stormwater basins. In the published literature, the GHG fluxes have only been quantified for bioretention basins and stormwater ponds [31–34] (Table 1). The reported values of GHG fluxes are presented in Table 1, for both bioretention basins and stormwater ponds.

Table 1: The GHG fluxes rates from two different WSUD basins (Positive and negative values represent GHGs uptake and emission respectively).

GHG fluxes (kg CO_2 eq. m^{-2} d^{-1})			**WSUD**	**Site characteristics**	**Ref.**
N_2O	**CH_4**	**CO_2**			
0.45×10^{-3}	-0.0088×10^{-3}	8.82×10^{-3}	Bioretention basins	Sandy loam, sandy loam, and compost, and mulch	[32]
0.052×10^{-3}	1.19×10^{-3}			Topsoil, native silt loam and a layer of sand	[33]
0.19 to 1.2×10^{-3}	13 to 48×10^{-3}	1.7 to 3.3×10^{-3}	Stormwater ponds	Duckweed Pond	[31]
	4.5 to 7.5×10^{-3}	0.63 to 1.5×10^{-3}		Duckweed Pond	[34]

Natural ecosystems such as natural and constructed wetlands have been widely studied for GHG fluxes [11], while this is not the case for vegetated stormwater basins in urban cities. This has important implications, as these stormwater systems have a close interaction with urban society and have a big impact on people's lives. Two studies have quantified the GHG fluxes of vegetated stormwater ponds using two different laboratory-scaled research investigations [31,34]. In both cases, these stormwater ponds were covered by duckweed.

Sims et al. [31], reported GHG fluxes of between 1700 and 3300 mg CO_2 m^{-2} d^{-1}, compared to 1472 and 626 mg CO_2 m^{-2} d^{-1} reported by Dai et al. [34]. Likewise, in the study of Sims et al. [31], CH_4 emissions ranged from 502 to 1900 mg CH_4 m^{-2} d^{-1} which is significantly higher than the two values of 299 and 180 mg CH_4 m^{-2} d^{-1}, in the study of Dai et al. [34]. A summary of the fluxes presented in Table 1. These CO_2 emissions are comparable to the average values of 93 and 237.3 mg CH_4 m^{-2} d^{-1} for various types of constructed wetlands reported by Mander et al. [10].

Nitrous oxide fluxes from stormwater ponds were found to be between 0.63 and 4 mg N_2O m^{-2} d^{-1} [31]. This is lower than the average value for N_2O emissions from various constructed wetlands, which ranged between 4.9 and 9.05 mg N_2O m^{-2} d^{-1} in the review by Mander et al. [10]. Nitrous oxide has 298 times more impact on global warming than CO_2, while methane has 25 times more impact than CO_2. Despite this difference, both studies have identified that methane has the most significant impact on GWP for stormwater ponds.

Bioretention basins are one of the most frequently used WSUD device. They are a vegetated depressed landscape area designed to filter the stormwater runoff through several engineered filter media [35]. The first GHG fluxes study on these basins was performed in the temperate coastal climate condition of Melbourne, Australia by Grover et al. [32]. Two bioretention cells with various filter media and with different saturated zone status were examined across soil water content and temperature. Their infiltration basins were slight sinks of CH_4, capturing between 0.12 and 0.58 mg CH_4 m^{-2} d^{-1}. This included cells both with and without a saturated zone, respectively. These results are similar to the average capture rate reported for dry detention basins by McPhillips and Walter, [33] (0.35 mg CH_4 m^{-2} d^{-1}). A summary of the fluxes presented in Table 1. Wetter soil profile basins decrease the likelihood of the basin acting as a sink of N_2O. Furthermore, it has been noted by McPhillips and Walter, [33] that this can also result in emissions of methane of up to 88.3 mg CH_4 m^{-2} d^{-1}.

Bioretention basins have been shown to be a slight source of N_2O under most conditions [32,33]. However, Grover et al. [32] discovered the occasional large emissions of N_2O. Grover et al., [32] and McPhillips and Walter, [33] demonstrated that unlike nitrous oxide, which has no clear temporal trend, carbon dioxide shows a positive correlation with temperature rise. The ability of bioretention basins to act as hotspots or sources of GHGs could have a substantial impact when scaled up and should be considered along with other ecosystem services and disservices provided by vegetated WSUD basins.

4 DISCUSSION

The carbon footprint associated with the emission of the three main GHGs shows a high variance between the reported values. The GHG fluxes is a dynamic field of study which can be influenced by a variety of parameters such as the age of the sites, solar radiation, air and water temperature, plant types and coverage [11]. On the other hand, the carbon footprint of the material production and construction phases has fixed values which occur at the time of the construction of the infrastructure. The operation and maintenance phase has a time dependent characteristic which must be assigned to a total life span. Based on the study of Kirk [36] the design life time of 30 years was considered for bioretention basins and stormwater ponds. The GHG fluxes were linearly extrapolated over a 30-year life time to be presented as a total carbon footprint.

The GHG fluxes from stormwater ponds vary significantly among the published studies (Table 1). The GHG fluxes from stormwater ponds determined in the current study have been shown to be between 107 and 334 kg CO_2 eq. m^{-2} over a 30 year life time. Methane is the greatest contributor to this result. Kirk, [36] has shown that stormwater ponds have a carbon footprint of 198 kg CO_2 eq. m^{-2}. This carbon footprint is associated with the four phases of material production (construction, operation and maintenance, and end-of-life), but does not include GHG fluxes. Figure 2 compares the minimum GHG fluxes potential of stormwater ponds with their reported traditional carbon footprint. Despite the high variance in GHG fluxes determined in the current study, they are significant when compared to the traditional carbon footprint by Kirk [36]. Hence, it is recommended that future studies investigate the total carbon footprint of these stormwater systems, including the direct GHG fluxes.

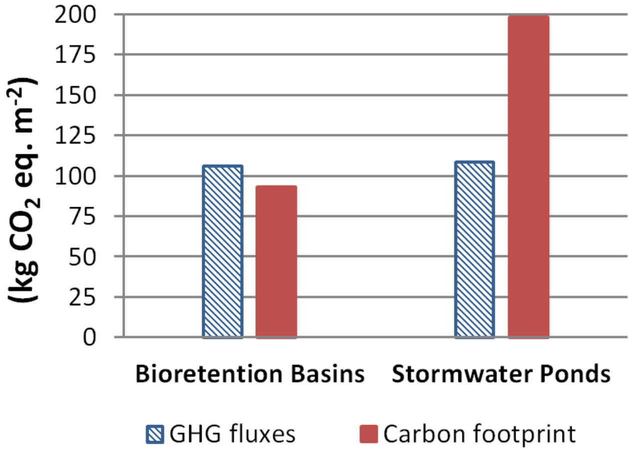

Figure 2. The carbon footprint and GHG fluxes of two different WSUD systems over a 30-year life span.

In bioretention basins, the 30-year carbon equivalent of methane and nitrous oxide have been computed as 4.8 and 13.6 kg CO_2 eq. m^{-2}, based on the published data by Grover et al. [32] and McPhillips and Walter [33]. At 96.5 kg CO_2 eq. m^{-2} over a 30-year life span, carbon dioxide has a significantly higher carbon footprint share than the other two gases. On the other hand, Kirk [36] has shown that the carbon footprint of bioretention basins is 93.3 kg CO_2 eq. m^{-2} over the 30-year life time. The combination of these results indicates that the fluxes of the three main GHGs from bioretention basins will be approximately 105 kg CO_2 eq. m^{-2} over a 30-year life span. It is important to note that the carbon footprint reported in studies such as that by Kirk [36] underestimates the total carbon footprint of bioretention basins by around 50% by ignoring the GHG fluxes. However, due to the scarcity of available data, more studies are required to investigate the GHG dynamics of these basins.

5 CONCLUSION

GHG fluxes from stormwater basins have been scarcely studied or reported in the published literature. Due to this limited available research on the GHG fluxes, the significant variance has been observed between the values presented in this literature. The findings of this study show that long term direct GHG fluxes from these stormwater basins can contribute to a large amount of the total carbon footprint. A linear extrapolation of values from the published literature over a 30-year life span indicates that direct fluxes from these basins can be noteworthy in comparison to the carbon footprint. The high variance in GHG fluxes from bioretention basins (13.6 and 101.3 kg CO_2 eq. m^{-2}) and stormwater ponds (158.1 and 569.3 kg CO_2 eq. m^{-2}) in 30 years point to the need for more research in this area. In contrast with direct GHG fluxes, the carbon sequestration potential of these basins can moderate the GHG emissions impacts.

Hence, future research on GHG fluxes and carbon sequestration of vegetated WSUD basins is essential to provide a comprehensive analysis of the carbon footprint. The results of such a consideration can provide policymakers and designers with the progressive inclusion of the total carbon footprint in the technical design characteristics of vegetated WSUD devices.

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