Ecological Engineering 58 (2013) 44–51

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Predicting the carbon footprint of urban stormwater infrastructure

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ARTICLE INFO

Article history:
Received 21 January 2013
Received in revised form 1 May 2013
Accepted 8 June 2013
Available online 6 July 2013

Keywords:
Carbon
Stormwater
BMPs
SCMs
Carbon sequestration
Carbon footprint
Carbon emissions
Stormwater wetlands
Bioretention
Swales

ABSTRACT

Due to increased regulations concerning urban stormwater runoff, stormwater control measures (SCMs) such as bioretention, ponds, and constructed stormwater wetlands, are becoming a more common feature of urban and periurban landscapes. The water quality and hydrologic benefits of SCMs are generally well-documented, and planning tools are available to optimize water quality benefits with economic costs of SCM construction and maintenance. Given rising interest in and potential for regulation of carbon emissions, a planning tool that allows for estimation of carbon emissions associated with SCM construction and maintenance is also a relevant pursuit. The objective of this work was to present a framework by which carbon emissions attributable to SCMs and conveyances could be predicted. This method was then applied to present a comparison of the carbon footprint of eight common SCMs and three stormwater conveyance types. The carbon embodied in construction materials represented a prominent part of the carbon footprint for green roofs, permeable pavement, sand filters, rainwater harvesting systems, and reinforced concrete pipes while material transport and construction dominated that of bioretention systems, ponds, wetlands, level spreader-grassed filter strips and concrete-lined swales. Despite accounting for sequestration by vegetation in these systems, only stormwater wetlands and grassed swales were predicted to store more carbon than what was released through construction and maintenance.

1. Introduction

Stormwater runoff from urban and residential land uses has been established as one of the leading contributors of non-point source pollution to downstream aquatic ecosystems. Increases in runoff volume and peak flows from urban and peri-urban areas are known to accelerate stream channel erosion and degradation, thus compounding the ecological impacts of runoff quality through alterations in aquatic habitat structure (Walsh et al., 2005). In recognition of these impacts, stormwater runoff is increasingly regulated at both the national (e.g. EPA NPDES Phase I and II stormwater regulations in the USA and Water Framework Directive in Europe) and local levels. Among the management strategies enforced by such regulations is the implementation of stormwater control measures (SCMs), also referred to as stormwater best management practices (BMPs), Sustainable Drainage Systems (SuDS), or as part of Water Sensitive Urban Design (WSUD). Structural SCMs may range from intensively engineered practices such as sand filters and permeable pavement systems to vegetation-based systems such as stormwater wetlands and vegetated filter strips in which the self-design principals of ecological engineering are made manifest.

For performance assessment and/or planning purposes, the economic costs of SCM construction and maintenance are often vetted against measured or anticipated water quality and quantity regulation benefits (e.g. Wossink and Hunt, 2003; Weiss et al., 2007; Davis and Birch, 2009). Given current efforts to both quantify and mitigate carbon emissions, carbon "costs" associated with SCM construction and maintenance should also be considered. To date, there have been studies to quantify carbon emissions associated with several types of SCMs. Green roofs in multiple climatic regions have been the subject of life cycle carbon emissions analysis (Getter and Rowe, 2009; Muga et al., 2008; Saiz et al., 2006). Kirk (2006) conducted a life-cycle greenhouse gas emission case study for a stormwater pond, gravel wetland, bioretention cell, and proprietary filtration system, though carbon sequestration by these systems was not considered. Similarly, Andrew and Vesely (2008) have examined carbon emissions for a sand filter and rain garden. Bouchard et al. (2013) examined roadside SCMs for carbon sequestration. Though individual SCM types and sites have been examined with respect to their so-called carbon footprint, there has not yet been a comprehensive tool developed by which to estimate carbon emissions and sequestration a priori from a variety of SCMs for planning purposes.

The objective of this work was to present a framework by which net CO_2 emissions (i.e. the carbon footprint) associated with the

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0925-8574/$ – see front matter
http://dx.doi.org/10.1016/j.ecoleng.2013.06.021

construction and maintenance of vegetated and non-vegetated stormwater infrastructure could be predicted. The framework also includes the potential for carbon sequestration in vegetated SCMs. Here, we have focused only the CO_2 component of the carbon footprint, following the preference of Wiedmann and Minx (2008) for carbon footprint accounting. This framework was then applied to a group of SCMs – including stormwater ponds, constructed stormwater wetlands (CSWs), bioretention cells, sand filters, level spreader-grassed filter strips (LS-VFS), concrete permeable pavement, green roofs, and rainwater harvesting systems – and stormwater conveyance systems – including reinforced concrete pipe (RCP), concrete channels, and grassed swales – to produce a side-by-side comparison on the basis of their carbon footprints. This work is intended to provide a framework for selecting and managing SCMs from a carbon standpoint.

2. Methods

The carbon footprint associated with each SCM and conveyance type was conceptualized as four components: (1) embodied carbon, defined as the CO_2 emissions associated with extraction and processing of the materials used in construction; (2) carbon emissions incurred during construction and (3) maintenance operations; and (4) sequestration of atmospheric CO_2 in vegetation biomass and soils through photosynthesis (Fig. 1). The net carbon footprint was calculated as the summation of carbon emissions associated with each of these components as follows: carbon footprint = embodied + construction + (maintenance − sequestration) × time. Maintenance emissions and carbon sequestration were considered on an annual basis and are thus multiplied by time (in years) to calculate the net carbon footprint for a desired time period.

A summary of the procedures, data sources, and assumptions used to estimate embodied, construction, and maintenance emissions is presented in Tables 1 and 2. Construction emissions included both transportation of construction materials and equipment to the site and emissions by construction equipment during operation. The distance traveled in the construction phase will vary by material and site location; to produce a relative comparison of SCM carbon footprints, round trip travel distance was held constant at 100 km (62 mi) for all materials and equipment. In the case of SCMs with major excavation requirements, it was assumed that 85% of excavated material was retained on site with the remainder being hauled a distance of 50 km (31 miles). Maintenance emissions included fossil fuel consumption during the transport of maintenance materials and crews to the site as well as maintenance equipment operation. Round trip travel distance was assumed to be 50 km for all maintenance-related travel. Assumptions regarding construction and maintenance transport vehicles are documented in the supporting information. All other assumptions regarding SCM maintenance are reported in Table 2.

Rates of carbon sequestration in urban vegetated systems were based on literature values. Organic carbon accumulation is not typically monitored in SCMs; therefore, when rates specific to an SCM were not available they were estimated based upon rates reported for comparable ecosystems (Table 3). With the exception of trees, which store carbon in aboveground biomass for long periods of time relative to grasses and emergent macrophytes, carbon sequestration in vegetated SCMs was estimated from published rates of soil carbon accumulation, which reflect the net result of photosynthetic carbon additions and losses through decomposition (Bruce et al., 1999). Longer-term storage in woody biomass was modeled for bioretention systems, which are commonly vegetated with trees or shrubs (USEPA, 1999a). Assumptions regarding required tree maintenance and lifetime (40 years) followed those outlined in the literature for species typified by moderate growth rates such as *Acer rubrum* (red maple), a tree commonly specified for bioretention systems (Hunt and Lord, 2006a,b). At the end of the trees' expected lifetime, it was assumed they were removed and mulched. Carbon emitted through decomposition of the hardwood mulch layer typically specified for bioretention cells was also included in computing the net carbon footprint of these systems. For calculation purposes, the mulch layer was assumed to be 5 cm thick (Hunt and Lord, 2006a,b) with a carbon content of 0.6 kg C kg^{-1} (Faucette et al., 2004). Mulch decomposition was assumed to follow a logarithmic decay curve, with complete decomposition of the mulch layer occurring within 20 years (Nowak et al., 2002). Carbon sequestration rates within sand filters, permeable pavement, and concrete conveyances were assumed to be negligible. Although ponds receiving high loads of allochthonous, sediment-borne carbon may sustain high rates of carbon accumulation in agricultural settings (Downing et al., 2008), accumulation rates in ponds in relatively low sediment yielding urban environments may only be significant in sediments of vegetated littoral areas (Moore and Hunt, 2011). Here, ponds and CSWs were assigned the same sequestration rate; for ponds, however, this rate was credited only to those areas that could be vegetated. Ponds were assumed to have a 3.1 m (10 ft) wide constructed littoral shelf following the recommendations in the USA (USEPA, 1999b). When evidenced in the literature, the time over which sequestration rates may be sustained was also accounted for. Declines in carbon sequestration rates over time have been reported for turf grasses (30 years; Qian and Follett, 2002) and green roofs (2 years; Getter and Rowe, 2009), reflecting the finite nature of soil carbon accrual and eventual equilibrium between carbon inputs and decomposition. Although rates of carbon sequestration by well-managed turfgrasses were found to be similar in both arid and humid regions (Milesi et al., 2005; Pouyat et al., 2009), it should be noted that rates of primary production and subsequent decomposition in other, non-irrigated or fertilized vegetated systems are controlled by climate, rainfall pattern, soil type and moisture regime, and other ecoregion-specific factors. The sequestration rates used in the present analysis are reflective of a temperate climate and may not be directly applicable to other climatic zones.

Given the time-dependent nature of maintenance emissions and carbon sequestration, net carbon emissions associated with a given SCM or other land cover type vary as a function of time. While routine maintenance activities (e.g. forebay cleanout) were considered over this period (Table 2), carbon emissions associated with the eventual decommissioning of SCMs at the end of their lifetime were not.

To produce a directly comparable carbon footprint, the functional unit upon which carbon footprint calculations were based was the surface area/volume of each SCM required to treat the first 25 mm of rainfall from a 100% impervious, 1-ha watershed. Since permeable pavement and green roofs do not typically treat additional run-on, the areas of these SCMs were set to 1 ha. The calculated size of each SCM and the associated quantity of materials required for construction are available in the supplementary information. Stormwater conveyances were also sized to convey a hypothetical discharge from a 1-ha impervious area. The peak discharge associated with this event was estimated using the Rational method and a design intensity of 177 mm h^{-1} (representative of a 10-year, 5-min storm intensity in Raleigh, NC, USA). The cross-sectional area of each conveyance type was then calculated using the Manning equation with an assumed Manning's roughness coefficient of 0.015, 0.013, and 0.025 for the RCP, concrete-lined channel, and grassed swale, respectively. Carbon footprint calculations for SCMs are reported in both kg CO_2-C ha^{-1} treated (i.e.