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Life cycle assessment of vertical and horizontal flow constructed wetlands for wastewater treatment considering nitrogen and carbon greenhouse gas emissions

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ABSTRACT

Life cycle assessment (LCA) is used to compare the environmental impacts of vertical flow constructed wetlands (VFCW) and horizontal flow constructed wetlands (HFCW). The LCAs include greenhouse gas (N_2O, CO_2 and CH_4) emissions. Baseline constructed wetland designs are compared to different treatment performance scenarios and to conventional wastewater treatment at the materials acquisition, assembly and operation life stages. The LCAs suggest that constructed wetlands have less environmental impact, in terms of resource consumption and greenhouse gas emissions. The VFCW is a less impactful configuration for removing total nitrogen from domestic wastewater. Both wetland designs have negligible impacts on respiratory organics, radiation and ozone. Gaseous emissions, often not included in wastewater LCAs because of lack of data or lack of agreement on impacts, have the largest impact on climate change. Nitrous oxide accounts for the increase in impact on respiratory inorganic, and the combined acidification/eutrophication category. The LCAs were used to assess the importance of nitrogen removal and recycling, and the potential for optimizing nitrogen removal in constructed wetlands.

1. Introduction and motivation

According to the National Academy of Engineering (NAE, 2008), one of the 14 Grand Challenges for Engineering for the 21st century is managing the nitrogen cycle. The NAE cites the needs to combat anthropogenic nitrogen fixation and subsequent water pollution, smog and acid rain, global warming, and associated environmental and human impacts, as the motivation for finding "countermeasures for nitrogen cycle problems". The challenge for engineers is to improve the effectiveness of human uses of nitrogen, including the biochemistry occurring within wastewater treatment plants.

In accordance with the recommendations of NAE, a wastewater treatment system should be designed for the least life cycle environmental impacts, including nitrogen emissions, and with the most potential for denitrification. Life cycle comparisons of conventional wastewater treatment (e.g., activated sludge technology) to constructed wetlands have shown that constructed wetlands cause less environmental impacts. However, these studies have not included gaseous emissions in

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their assessments nor have they specified constructed wetland designs that differ significantly in size or treatment capacity.

LCA is used herein to assess the environmental impact differences in constructed wetland design by comparing a hypothetical horizontal flow system to vertical flow. Other findings from the LCA include how to account for wastewater treatment gaseous emissions; whether constructed wetlands emit less greenhouse gases than conventional treatment; which constructed wetland life stages have the greatest impact; and which design, operational and management variables could be adjusted to reduce environmental impacts. Furthermore, the analysis allows for considering potential tradeoffs in environmental impact between global and local scales. Although these results are comparable to other reported wastewater LCAs, this work quantifies the impacts specifically related to nitrogen emissions from constructed wetlands.

2. Background

2.1. *Wetland greenhouse gas emissions*

Vertical flow constructed wetlands (VFCW) are efficient at converting wastewater ammonium to nitrate and also effective in denitrification (Fuchs, 2009a). Because of the efficient oxygen transport of a VFCW, its physical footprint can be much smaller than a horizontal flow constructed wetland (HFCW) designed for the same effluent quality (Brix and Arias, 2005). Constructed wetlands have also been shown to produce less environmental impacts over the life cycle compared to conventional wastewater treatment plants (Dixon et al., 2003; Machado et al., 2007).

Wetland researchers (listed in Table 1) have measured greenhouse gas emissions of CO_2, CH_4, and N_2O from both VFCWs and HFCWs. The quantity and impact of all these gases are important because CH_4 has 25 times the global warming potential of CO_2 and N_2O has 298 times the global warming potential of CO_2 (IPCC, 2007). Table 1 lists reported effluent and areal emissions pertaining to different influent parameters. The range of reported emissions is large (emissions are related to seasonal and other environmental conditions) and the areal emissions from VFCWs are generally higher. Sovik et al. (2006) found that VFCWs had significantly higher areal gaseous emissions than HFCWs, and gas emissions were correlated to temperature, substrate supply (influent N and C concentrations), and degree of oxidation in the wetland.

2.2. *Life cycle assessment*

LCA is a comprehensive and transparent tool for estimating potential environmental impacts of products and processes (UNEP, 2009). LCA can be used in the design phase for choosing between technologies with similar performance by accounting for the impacts caused by each technology over its life cycle. For example, researchers have compared conventional activated sludge wastewater treatment to constructed wetlands using LCA. Dixon et al. (2003) found that constructed wetlands have less global warming potential (CO_2 emissions) and less energy use than conventional treatment. Machado et al. (2007) found that wetlands also reduced aquatic toxicity and eutrophication compared to conventional activated sludge wastewater treatment.

LCA can also be used to identify which life stage carries the most significant environmental impacts for particular designs or classes of designs. LCA on wastewater treatment indicates that the life cycle impacts of the operation phase are much greater than the construction phase for conventional activated sludge treatment systems (Tillman et al., 1998; Lundin et al., 2000; Dixon et al., 2003; Emmerson et al., 1995; Ortiz et al., 2007; Renou et al., 2008). For constructed wetlands, however, the construction phase dominates the life cycle impacts due to the amount of materials transported for construction as well as the reduction of energy use during operation (Dixon et al., 2003; Machado et al., 2007).

Only two LCAs considered nitrogen emissions in the wastewater treatment life cycle, but the emissions were only counted from fuel use, not from wastewater nitrogen transformation

Table 1 – Influent and effluent water quality and gaseous emissions of N_2O, CO_2, and CH_4 reported for vertical flow and horizontal flow wetlands.

	Influent (mg/L)			Effluent (mg/L)		Emissions (mg/m^2/d)		
	TN–N	NH_4^+–N	BOD	NH_4^+–N	NO_3^-–N	N_2O	CO_2	CH_4
Vertical flow constructed wetlands								
Zhou et al., 2008						−1.4 to 188		
Inamori et al., 2007	9.8	8.1	38			<0.24		<72
Inamori et al., 2007	18.4	10.2	60			<0.48		<240
Inamori et al., 2007	36.7	19.3	163			<1.44		<480
Sovik et al., 2006 (Koo VFCW)	50.9	35.7	142	31.7	1.7	10.8[a]	5200[a]	77.4[a]
Horizontal flow constructed wetlands								
Maltais-Landry et al., 2009	21.7	0.18		0.2 (g/m^{2}d)	0.05 (g/m^{2}d)	3	1400	5
Fey et al., 1999			500			3.2		
Sovik et al., 2006 (Kodijarve wetland)	96.5	83.9	125	36.2	5.9	4.5[a]	2490[a]	182[a]
Sovik et al., 2006 (Koo wetland)	43.1	31.7	62.8	34	1.2	2.9[a]	1301[a]	96.5[a]

Yearly average = [summer average (#samples) + winter average (#samples)]/total #samples
a Yearly average calculated from reported summer and winter data.