TECHNICAL NOTE:

THE POTENTIAL OF MUNICIPAL YARD WASTE TO BE DENITRIFICATION BIOREACTOR FILL

L. E. Christianson, N. Hoover, A. Bhandari, M. J. Helmers

ABSTRACT. *The use of denitrification bioreactors to mitigate nitrate in agricultural drainage has recently gained much interest in the Midwestern United States and in similarly drained agricultural regions. However, as the number of bioreactor installations has increased, questions have been raised about the supply and consistency of denitrification carbon source material. In selecting such material, there is an important balance between optimal media properties (e.g., hydraulic properties, chemical composition), practicality, and material cost. The use of free material such as municipal yard waste may help minimize the cost of this voluntary water quality improvement strategy in the Midwestern United States, but may not provide other sufficient media properties. To investigate this, pilot-scale bioreactors were used to compare hardwood chips with free, chipped municipal yard waste in terms of nitrate removal potential and changes in the media. Sampling of bioreactor influent and effluent over a range of retention times showed the yard waste had higher removal efficiencies at a given retention time and higher removal rates than the woodchips. However, buried carbon media bags revealed the yard waste lost weight to a greater extent and more consistently than the woodchips meaning the woodchips had a half-life over two times greater than the yard waste. This, combined with the low carbon-to-nitrogen ratio of the yard waste, indicated yard waste material is not ideal for bioreactor installations that are intended to be low maintenance for at least ten years.*

Keywords. *Denitrification bioreactor, Agricultural drainage, Woodchip, Yard waste, Nitrate.*

In the Midwestern United States, denitrification bioreactors for agricultural drainage have shown potential as a useful technology for reducing nitrate (NO_3^-) in surface waters (Woli et al., 2010; Christianson et al., 2012). Inside these edge-of-field excavations, carbon-based fill media is utilized by native denitrifiers as they convert nitrate in drainage water to nitrogen gas when anaerobic conditions are maintained at a sufficiently long retention time. For drainage bioreactors to provide maximum water quality benefit, they must be practical in a farm setting. Important factors affecting bioreactor practicality and performance include the carbon media selected to fill the reactor and its ability to support sustained, enhanced denitrification over the estimated several decade bioreactor life (Moorman et al., 2010; Schipper et al., 2010; Long et al., 2011). The physical, chemical, and biological properties of the media affect overall bioreactor performance through factors such as hydraulic conductivity, porosity, carbon: nitrogen ratio (C:N), microbially available carbon, and longevity. Additionally, potential negative side effects such as leaching of organic carbon and nitrogen must be considered. In selecting a carbon source material, there is an important balance between optimal media properties, practicality, and material cost.

Though these treatment systems have colloquially been termed "woodchip bioreactors," material other than woodchips has been investigated as a denitrification bioreactor carbon source. Cardboard, corn stalks, shredded newspaper, and walnut and almond shells, among many other materials, have been tried under a variety of research-scale conditions with varying NO_3^- removal results (Volokita et al., 1996; Diaz et al., 2003; Greenan et al., 2006). In a comparison of cornstalks, cardboard, and oak chips, Greenan et al. (2006) found cornstalks had the highest NO_3^- removal rate though the rate seemed to decline over the 180-day batch experiment. Similarly, Soares and Abeliovich (1998) reported wheat straw supported high rates of NO_3^- removal, although this could not be sustained without periodic additions of fresh straw. In a study of five types of carbon media, Cameron and

Submitted for review in March 2012 as manuscript number SW 9679; approved for publication by the Soil & Water Division of ASABE in September 2012. Presented at the 2011 ASABE Annual Meeting as Paper No. 1111036.

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Schipper (2010) found wheat straw and maize cobs initially released outflow streams with the greatest amounts of ammonium (NH_4^+) and biological oxygen demand (BOD), though these treatments also had higher NO_3^- removal rates than wood treatments. Likewise, Gibert et al. (2008) found treatments of mulch and compost to be unsuitable because these materials either leached significant amounts of nitrogen (N) or encouraged dissimilatory reduction of NO_3^- to NH_4^+ rather than denitrification. Most recently, Warneke et al (2011) suggested a mixture of media types such as maize cobs and woodchips may help minimize negative side effects (e.g., leaching of organics) while helping maximize beneficial microbial properties.

With denitrification bioreactors for agricultural drainage receiving increased attention as a water quality improvement strategy across the Midwestern United States, engineers and environmental professionals are now trying to identify the most practical locally available sources of carbon material. In this context, one potentially readily available bioreactor carbon source is municipal yard waste. Municipal yard waste/storm debris could be a very convenient fill material as it is often considered a waste and is usually free or very low cost. Many towns and individual farms have such materials that could be easily chipped on-site for use as bioreactor fill. Based on past literature, this labile carbon source may be able to support high rates of NO_3^- removal though detrimental side effects also need to be investigated. Additionally, from a design standards perspective, it may be important that such yard waste supplies will likely be very heterogeneous between, and even within, piles due to local vegetation and chipping capabilities. The objective of this work was to determine if municipal yard waste was comparable to woodchips in terms of NO_3^- removal and media composition for drainage denitrification bioreactor applications.

METHODS

Three pilot-scale denitrification bioreactors of different shape, as described in Christianson et al. (2011), were used for a comparison of enhanced denitrification fill media. These channel, rectangle, and trapezoidal designed bioreactors (volume: 0.71m^3, fill depth: 0.6m) were filled with woodchips for media testing in 2009 and municipal yard waste for testing in 2010 (fig. 1). See Christianson et al. (2011) for details on bioreactor construction, design, and NO_3^- removal results with woodchips from the first year of operation. The woodchips, described as a mixture of hardwood species, were purchased from a local supplier (\$20 per 0.76m^3) and had 54% of particles by weight fall in the 13- to 25.4-mm size range (Christianson et al., 2010a; Christianson et al., 2011). Bioreactor installation and woodchip filling occurred on 8 December 2008, roughly 5.5 months before operation began.

The yard waste for this investigation was obtained free of charge from the Parks & Recreation Department (Ames, Iowa) on 18 November 2009. Though the bioreactors were filled with this media in November 2009, bioreactor operation began 5.5 months later in May 2010 when they began receiving drainage water at a controlled flow rate from an underground storage reservoir. During summer 2010, the flow rates were manipulated to obtain a range of bioreactor retention times (1.8 to 9.5 h, based on average flow depths) and influent and effluent grab samples from the bioreactors were collected for NO_3^--N analysis. These retention times compared well with the woodchip testing retention times which ranged from 1.3 to 12.0 h. The testing of the two media types was also performed for similar lengths of time and during similar seasons; the woodchip testing ran for 154 days (22 May to 23 October 2009), while the yard waste testing ran for 138 days (5 May to 19 September 2010). Moreover, the range of influent nitrate concentrations was similar in the two years (woodchip year influent: 9.7 to 12.3 mg NO_3^--N/L).

To measure and calibrate the inflow and outflow rates, a stopwatch and graduated cylinder were used to measure the volume of these flows during a pre-determined time interval. The outflow rate was used to calculate the retention time except during 4 May to 17 May and 16 June where only inflow readings were taken (i.e., inflow rate used to calculate retention time on these dates). Retention time was calculated based on the active flow volume multiplied by the media porosity divided by the bioreactor flow rate. The active flow depth used to calculate the active

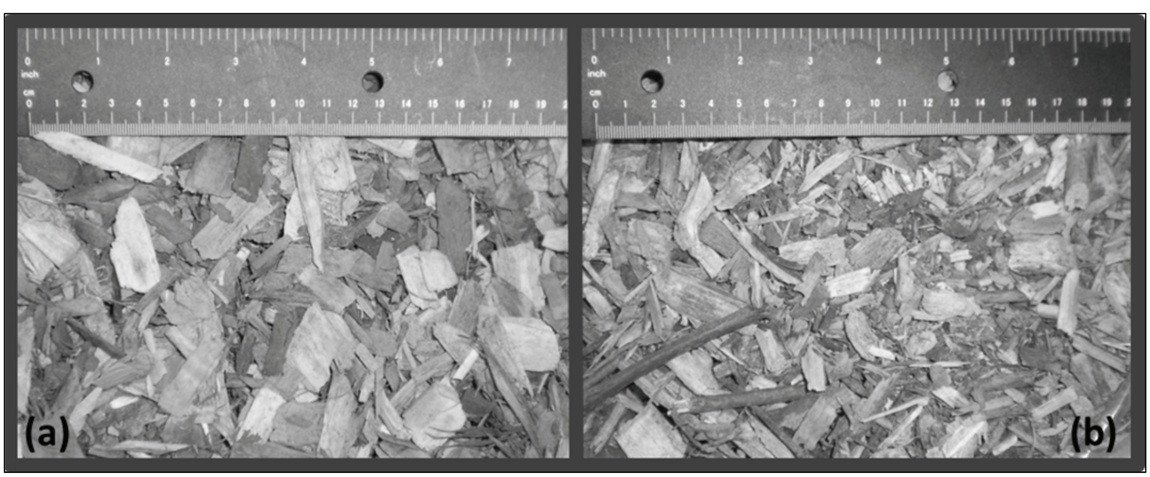

Figure 1. Woodchips used in pilot bioreactor study performed in 2009 (a) and yard waste studied in 2010 (b).

media bed volume was an average of flow depth measurements collected over the operational period; these depths were measured in PVC piezometers (2.5 cm diameter) installed in each reactor. Water temperature was measured with a Fisher Scientific Traceable® thermometer (Waltham, Mass.) in the drainage water reservoir on each sampling date. Influent and effluent samples (acidified) were stored at 4°C until they were analyzed for NO_3^--N using a colorimetric method with a Lachat Quick-Chem 8000 automated analyzer (Standard Methods, 1998).

During bioreactor filling in 2009 and 2010 with woodchips and yard waste, respectively, media bags were prepared in the laboratory using polyester drain sleeve filter fabric and zip ties. Six bags filled with approximately 138±14 g (dry weight) of media each were placed in each reactor with three within 5 cm from the bottom and three within 5 cm from the top of the media under the bioreactor soil cover layer. The bags were weighed before installation in the bioreactors and also after all testing had been completed for each media type (i.e., pre- and post-operation). To account for moisture content, a selection of media taken during bag filling was dried at 70°C until reaching a constant weight (pre-bioreactor operation) and the harvested bags were similarly dried (post-operation). Neither pre- nor post-operation chips were washed before weighing to avoid the loss of fines. After harvesting the media bags, yard waste and woodchips from these bags were analyzed for organic carbon (C) and total nitrogen content (N) (combustion analysis, ISU Soil and Plant Analysis Laboratory); both media types were also analyzed for C and N in their initial condition. Porosity of the yard waste was measured using methods used to determine woodchip porosity described in Christianson et al. (2010a) (taken from Ima and Mann, 2007) where the void space of a set volume of media was filled with water, the weight of which was then equated to porosity after a period of approximately 24 h.

RESULTS

WATER QUALITY PARAMETERS

Site flooding in early June, early July, and early August 2010, complicated testing of the pilot bioreactors which were installed in the ground. The high frequency of precipitation events and the especially large events in August 2010 inhibited sampling during these periods (fig. 2b). To minimize potential lingering data effects from these events, samples from 6 to 21 August were removed from analysis. Additionally, samples from the rectangle bioreactor collected in September 2010 were excluded as this reactor became saturated with standing water

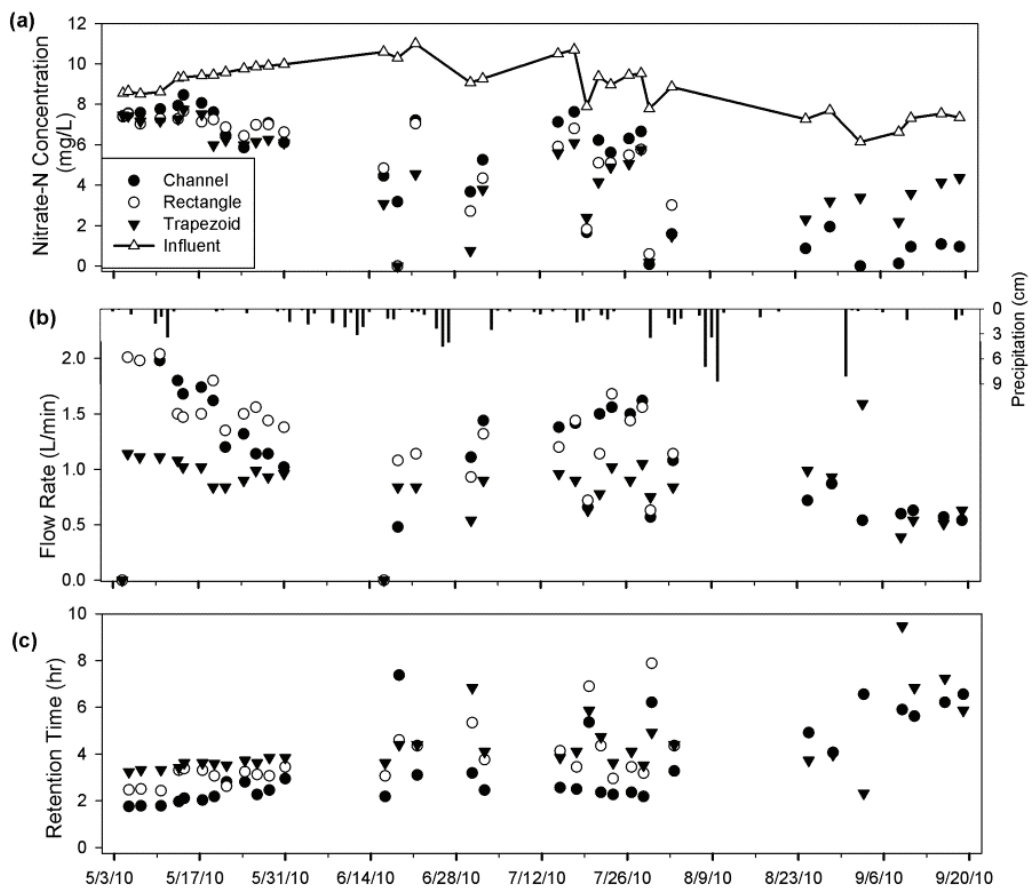

Figure 2. (a) Influent and effluent NO_3^--N concentrations, (b) corresponding flow rates and precipitation, and (c) associated retention times for three pilot-scale bioreactors filled with municipal yard waste operated during summer 2010 in Iowa. September 2010 rectangle bioreactor samples were excluded due to bioreactor malfunction.

potentially due to plugging. In terms of the water balance, including all rain events, the rain volume falling directly on the reactors during the testing period was less than 2% of the total flow volume and was thus considered negligible (total of 87 cm of rain); during the woodchip testing the previous year, the rain volume falling on the reactors was 0.6% of the total flow volume (31 cm total rain).

The municipal yard waste was a sufficient carbon source to support NO_3^--N removal from the drainage water in the 138 d of pilot bioreactors operation (fig. 2a). In general, there was little difference between influent and effluent NO_3^--N concentrations when flow rates were relatively high in the beginning of testing, whereas greater concentration reductions were observed towards the end of testing at lower flow rates (fig. 2 a and b). These higher flow rates at the beginning of testing correlated with retention times of 1.8 to 3.8 h for the three bioreactors; over the test, the retention times were gradually increased from these initial values to 8.3 - 9.5 h (fig. 2 b and c). It was likely the low removals initially were due to the relatively lower retention times rather than slow start-up of the denitrifying community as no inoculation of denitrifiers has been required to date (Schipper et al., 2010).

Expressing these N reductions in terms of the mass of N removed showed the percent mass reduction correlated with retention time (fig. 3). This relationship was also documented, albeit more clearly with a higher R^2 value, with the woodchip-filled bioreactors (fig. 3, from Christianson et al., 2011). The yard waste linear regression slope of 11.1% per h was higher than the regression slope for the woodchips (8.4% per h) indicating the yard waste had a higher removal potential at a given retention time. This increased NO_3^--N removal potential due to more labile-carbon reactor fill has been documented by others, but it may be short lived and may require fresh media additions (Soares and Abeliovich, 1998; Park et al., 2009; Schipper et al., 2010). It's important to note that here, sustainability of the fill materials and longer term N removal (i.e., greater than approximately five months) were not evaluated.

Similar to this regression analysis, the yard waste had higher volume-based N removal rates than the woodchips. The woodchip-filled bioreactors exhibited average removal rates of 3.8 to 5.6 g N/m^3/d with water temperatures ranging from 10.5°C to 15.4°C (Christianson et al., 2011). With mean values of 7.5 to 8.4 g N/m^3/d, the yard waste had significantly higher removal rates ($p = 0.0047$), though water temperatures ranged slightly higher at 9.4°C to 20.9°C during the 2010 yard waste tests. These ranges of removal rates have been documented at field-scale bioreactors with Woli et al. (2010) reporting 6.4 g N/m^3/d for a biofilter in Illinois and Christianson et al. (2012) reporting a maximum value of 7.76 g N/m^3/d from a multiple year comparison of four bioreactors in Iowa.

Carbon Media Parameters

The porosity of the yard waste ranged from 62% to 69% (mean: 66% ± 3.9%) at packing densities of 199 kg/m^3 to 178 kg/m^3, respectively. This porosity was similar to, but slightly lower than the 66% to 78% reported for woodchips at packing densities between 250 and 190 kg/m^3 (Christianson et al., 2010a). The average porosity of 66% was also comparable with Ima and Mann's (2007) woodchip porosity of 63% at a packing density of 286 kg/m^3 (40% moisture content; 59% of particles in the 6.7 to 25 mm size range) and to field estimates of 70% for coarse woodchips in a reactor in Canada (1-50 mm size; van Driel et al., 2006) and 65% for woodchips in a bioreactor in Illinois (62% of particles between 6.3 to 25.4mm; Woli et al., 2010). Though no particle size analysis was performed on the yard waste, visual observation showed this media generally had smaller particle sizes than for the woodchips (fig. 1).

Visual observation of media bags harvested from the reactors revealed differences based upon bag location as well as media type. The yard waste in the bags located in the top of the bioreactors was notably darker in color than the waste in the bottom-placed bags; this was possibly due to the dark bioreactor cap topsoil settling amongst the material (i.e., a possible side effect of site flooding). The woodchips from the bags placed in the bioreactor top section were consistently observed to have white growth present on them whereas no such growth was observed on the woodchips in the bottom-placed bags or yard waste

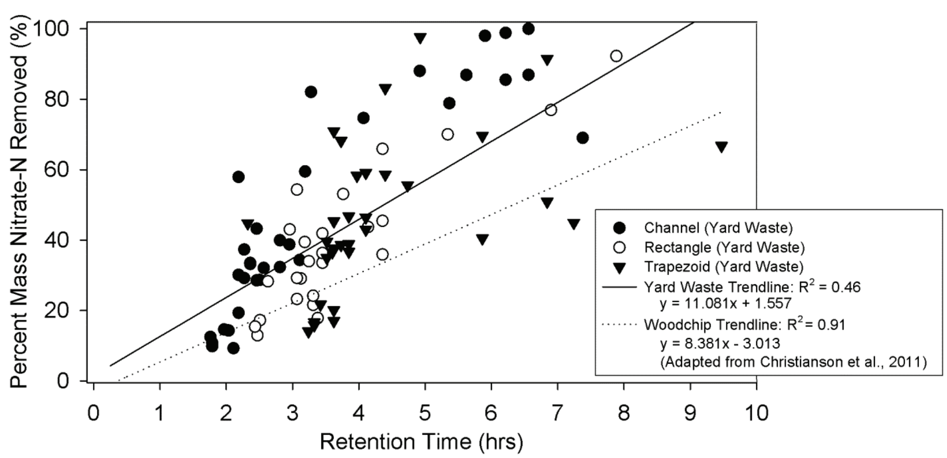

Figure 3. Retention time correlation with percent mass NO_3^--N removal for three pilot-scale bioreactors.

bags. The post-operation yard waste bags had notably greater amounts of very fine material (approximately <2 mm) compared to the post-operation woodchip bags.

The media bags also showed the yard waste lost weight to a greater extent and more consistently than the woodchips (fig. 4). When the bioreactors were operated with woodchip fill, only the media bags placed in the top of the reactors showed weight loss. This top section would normally have been unsaturated, and thus, the weight loss was attributed to aerobic degradation of the material also reported by Moorman et al. (2010) in woodchip denitrification treatment walls. Conversely, the woodchip-filled bags in the bottom of the bioreactors consistently showed weight gain. This may have been a result of potentially overlooked microbial or fungal growth.

When the bioreactors were operated with yard waste, all the media bags lost weight regardless of placement, and the yard waste bags in the top of the reactors lost significantly more weight than the bottom-place bags ($p < 0.0001$; fig. 4). The weight loss consistently documented in all the yard waste bags indicated potential for shortened life of reactors filled with this material compared to woodchip material. When this weight loss information was combined with removal rates for the two medias, the woodchips showed slightly better efficiencies; based on the weight lost averaged from the top and bottom-placed bags, the yard waste lost 3.8±1.1 g bag weight per g N removed per day and the woodchips lost 2.4±1.6 g bag weight per g N removed per day. Note, these results may have been complicated by the lag time between installation of the yard waste in Fall 2009 and operation in Summer 2010. Additionally, recall weight loss effects may have been complicated by the flooding conditions experienced by the yard waste.

In terms of reactor design, while there were no significant differences between the three yard waste-filled bioreactors in percent mass N removal or in N removal rate ($p = 0.35$ and $p = 0.57$, respectively), the yard waste media bags installed in the channel-designed bioreactor had a

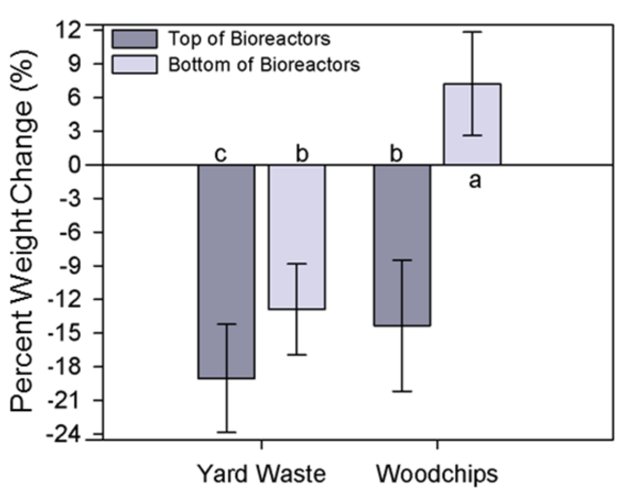

Figure 4. Weight change in buried media bags containing woodchips or yard waste after pilot bioreactor operation; means with the same letter are not significantly different ($\alpha = 0.05$; $n = 9$).

significantly higher percentage of weight loss than the trapezoidal bioreactor bags (means -20% and -12%, respectively; rectangle-designed yard waste bags: -16%) (data not shown). This may have been due to the channel bioreactor's highest (non-significant) mean percent mass N removal and mean removal rate. However, the lack of significant difference in N removal performance further corroborated the design evaluation performed the previous year showing inconsistent differences in N removal between the three designs when filled with woodchips (Christianson et al., 2010b).

Theoretical half-lives of these two media types were calculated from these weight loss data using a linear regression to model decay and test lengths of 154 and 138 d for the woodchips and yard waste, respectively. A linear regression was used as only two weight values (pre- and post-bioreactor operation) were available for each media. The top layer of the woodchips and yard waste had half-lives of 1.5 and 1.0 yr, respectively. The bottom layer of the yard waste had a half-life of 1.5 yr and a half-life was not calculated for the bottom layer of the woodchips as this material did not lose weight. If the top and bottom layers were averaged for each media with 0% weight loss substituted for the woodchip bottom layer, the overall half-lives for the woodchip and yard waste bioreactors were 3.0 and 1.2 yr, respectively. Similar calculations based on weight loss in a woodchip wall by Moorman et al. (2010) showed half-lives of 4.6 and 36.6 yr for shallow and deep layers, respectively (assuming first order decay). The longer half-lives of the bottom layer for both media types here further corroborated that maintaining a significant thickness of saturation in the bottom of the reactor may help increase bioreactor life regardless of fill material.

The best-case scenario of a 3-yr half-life calculated here does not reflect that many existing woodchip denitrification systems have had lives longer than this. Empirical evidence from a woodchip wall and a sawdust wall indicates these systems continue to reduce NO_3^- from groundwater 9 and 14 yr after installation, respectively (Moorman et al., 2010; Long et al., 2011). Long et al. (2011) estimated total carbon in the wall would be sufficient for 66 yr, though it was not known at what level denitrification would become carbon limited. Moreover, drainage denitrification bioreactors similar to this pilot work have been operating in Illinois since 2007 (Verma et al., 2010) with one in Iowa operational since 2004 (Christianson et al., 2012).

The potential cost and effort of frequently refilling bioreactor material could be onerous as Christianson et al. (2012) indicated that the total establishment cost of a bioreactor ranged from \$195 to \$586 per ha treated of which the woodchip cost comprised 13% to 55% (mean: \$132±57 per ha) and the contractor fees comprised 23% to 54% (mean: \$155±\$90 per ha). One of the largest advantages of using yard waste or chipped storm debris as bioreactor fill is that in many cases it may be available free of charge, likely with only a small transport fee. Because both the material and contractor/labor components represent significant costs of installation, even if the material were free of charge, the increased frequency of labor costs for material replacement may be considerable.

Based on the half-lives calculated here, the yard waste would need to be replaced approximately 2.5 times more frequently than the woodchips (i.e., 3.0 yr divided by 1.2 yr). In other words, within a hypothetical 6-yr period, a woodchip bioreactor would need replacement twice at approximately $574 per ha (two times the sum of $155 per ha and $132 per ha), whereas a yard waste bioreactor would require material replacement five times costing $775 per ha (five times $155 per ha, neglecting material transport costs). Additionally, these approximations do not reflect extra effort and time required of the landowner for more frequent material replacement even if a private contractor is used. This is a notable consideration as the practicality and minimal maintenance of bioreactors are important relative advantages of this water quality improvement option.

Media bags of both types in both locations generally had decreased mean percentages of carbon and increased mean percentages of nitrogen over the course of bioreactor operation (fig. 5). For carbon, the only significant difference was a decreased percentage after bioreactor operation in the bottom-placed yard waste bags. However, for both media types, the increase in percent nitrogen was significant for the top-placed media bags. Additionally, the bottom-placed yard waste had a significantly higher percentage of nitrogen than the initial yard waste, though significantly less than the post-operation top-placed yard waste bags.

With a carbon-to-nitrogen ratio (C:N) of 77±5, the yard waste had an initial C:N lower than the purchased woodchips (woodchip C:N 251±37). This low C:N of the yard waste was due to its significantly higher nitrogen content (fig. 5). Diaz et al. (2003) noted that materials with relatively high C:Ns are good substrates for solid-source enhanced denitrification as they provide sufficient organic carbon without potentially increasing the nitrogen concentration in solution. Low C:N bioreactor media such as materials including leaves and conifer needles is not recommended as this material may ultimately leach nitrogen (unpublished data). After bioreactor operation, both materials experienced decreases in C:Ns, a trend that has been documented in other denitrification media comparisons. In an eight-month denitrification study, Diaz et al. (2003) noted a decrease in the C:N of walnut shells from 247 to 158 that was attributed to the release of organics and correlated with high rates of NO_3^- removal. Similarly, Saliling et al. (2007) documented that woodchips and wheat straw had decreased C:Ns (394 to 185 and 135 to 37, respectively) after several months of denitrification. Here, the C:N typically decreased more in the top-placed bags corroborating the weight-loss and microbial activity in that layer.

CONCLUSIONS

Although yard waste (i.e., municipal storm debris) provided sufficient carbon for short term use in a pilot-scale denitrification bioreactor for agricultural drainage, there was serious concern regarding the longevity of this material based upon the percent mass loss compared to woodchips over one season of operation. While the yard waste provided higher N removal at a given retention time and had higher overall removal rates, its calculated half-life was less than half that of woodchips. The potential need for frequent replacement of such low C:N media is contrary to the notion these systems are intended to be low maintenance for at least a decade. Though these results were complicated by non-ideal field conditions, yard waste as bioreactor fill is likely not ideal for sustained bioreactor use despite the low cost of this material. Additionally, regardless of bioreactor fill, the ability to maintain a deep saturated layer within the bottom of the bioreactor may help extend the life of the media. Suggested future work stemming from these results includes development of performance criteria for bioreactor media, better understanding of long-term effectiveness of media *in situ*, and criteria for final disposal of utilized carbon media.

ACKNOWLEDGEMENTS

The authors acknowledge Manu Ajmani and Ryan Nelson for their assistance with the field aspects of this project and Dan Andersen for help with the laboratory grinder. Funding for this work was provided by the Leopold Center for Sustainable Agriculture. The corresponding author's time was funded through a USDA NIFA Pre-Doctoral Fellowship Grant (Agriculture and Food Research Initiative Competitive Grant no. 2011-67011-30648 from the USDA National Institute of Food and Agriculture). This article was expanded upon from proceedings paper number: 1111036 presented at the 2011 ASABE Annual International Meeting in Louisville, Kentucky.

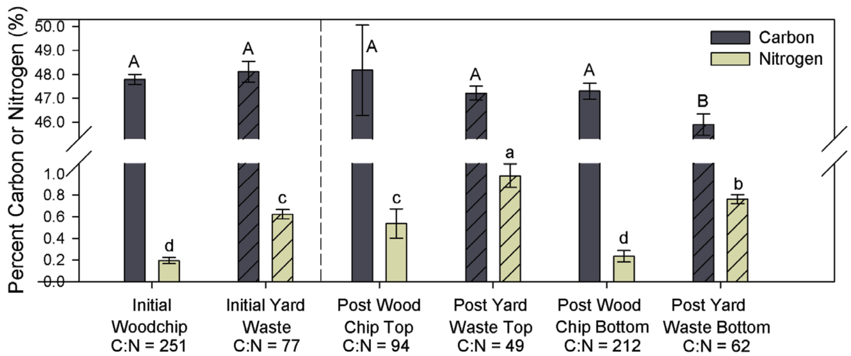

Figure 5. Percent carbon and nitrogen of media bag yard waste and woodchips, both before and after pilot bioreactor operation; means with the same letter are not significantly different (α = 0.05; n = 3 with each sample analyzed as a duplicate).

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