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Applying trait-function relationships for microbial plant decomposition to predict medium longevity in pollution control biofilters

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Abstract Biofilters, bioreactors used for pollution control, can effectively treat a variety of odorous and hazardous emissions, but uncertain medium longevities and associated costs limit biofilter adoption. To improve medium-life estimations for biofilter end-users, litter bags were used to compare decay rates of common biofilter medium types and test the effects of nitrogen (N) enrichment and livestock production emissions on medium decay in a full-scale biofilter over a 27-month period. Generally, "by-product" media (mulch, corn cobs) decayed faster than hardwood media, with decay of softwood media the slowest. Analysis showed nutrient content was the best predictor of early-stage decay, while carbon fractions and nutrient content best predicted medium longevity. N amendments and N-rich barn emissions were found to hasten medium decay. By identifying decay rates and rate predictors specific for biofilter media, we provide biofilter engineers and farmers with a quantitative way to improve medium selection based on the trade-offs between medium cost and replacement frequency.

Keywords Bioreactor · Media · Decay rate · Litter bag · Nitrogen

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Introduction

Packed-bed bioreactors using organic media (e.g., wood mulches) are promising control technologies for treating aqueous (Schipper et al. 2010) and gaseous (Chen et al. 2009) pollution. For gas-phase biofilters, removal efficiencies can exceed 90 % for odor, ammonia (Chen et al. 2009), and petroleum-based volatiles (Prenafeta-Boldú et al. 2012), and range from 20 to 85 % for the greenhouse gas methane (Veillette et al. 2012). In aqueous-phase bioreactors, removal efficiencies for nitrate can range from 50 to 100 % depending on loading (Robertson 2010). Both these bioreactor systems utilize microbial growths on a solid packing medium (biofilms) to degrade pollutants from contaminated effluents. Harnessing biofilms for waste mitigation offers several advantages, including (1) pollutant breakdown to non-hazardous products, (2) natural acclimation (adaptation) to the effluent, and (3) simultaneous treatment of many pollutants over a range of concentrations, all for a relatively low cost (Cabrol and Malhautier 2011).

In the case of gas-phase biofilters for agricultural systems, construction and operational costs are completely within a farm budget (Delhomenie and Heitz 2005) and design flexibility enables end-users to customize and self-construct biofilters for their specific operational needs (Schmidt et al. 2004). Though well suited for farms, building a biofilter does not guarantee barn and manure storage emissions are efficiently controlled as loading rates, abiotic conditions, and microbial communities also affect performance (Chen et al. 2009). While biofilters must be managed for optimal performance, minimally managed biofilters can still be effective as biofilms can tolerate and adapt to shutdown periods, shock loading (Cabrol and Malhautier 2011), low nutrients, pH stress, dry conditions, and novel emissions (Kennes and Veiga 2004). Despite management intensity and biofilm robustness,

irreversible loss in biofilter performance will ultimately result due to biofilter medium breakdown, compaction, and the associated channeling and blockage of airflow (Chen and Hoff 2009). This physical failure of biofilters is a consequence of biofilm growth and microbial degradation and is only corrected through refreshment or replacement of the medium, an unpredictable cost of biofilter maintenance and a potential barrier to wider adoption of the mitigation technology.

Long-lived, engineered medium types have been developed to target regulated, non-agricultural effluents (Prenafeta-Boldú et al. 2008), but these media have high costs (Dorado et al. 2010a) which has limited their adoption by US livestock producers. On US farms where biofilter usage is largely voluntary and cost significantly limits more widespread biofilter usage, inexpensive wood mulch media are commonly used (Chen et al. 2009; Schmidt et al. 2004), with use of agricultural by-products, not engineered media, likely in the future (Akdeniz et al. 2014; Ramirez-Lopez et al. 2003). Currently, the useful life of wood mulches as biofilter media is estimated at 5 years based on observational estimates, but is often less (Chen et al. 2009; Schmidt et al. 2004), and the longevity of agricultural by-products (e.g., corn cobs) as biofilter media is unknown. Knowing or predicting the actual useful life of these organic media is essential, however, to ensure biofilter maintenance costs are accurately anticipated and farmer interest and confidence in biofilters are not lost. While the effects of environmental conditions, moisture content (Chen et al. 2009), emission loading (Lebrero et al. 2014), and medium physical conditions (Dorado et al. 2010a) on medium utility have been thoroughly explored, the effect of medium traits on the longevity of organic medium types has not been well addressed. This is despite a clear linkage between traits and decay of organic materials in natural systems (Prescott 2010) which would suggest a dense low-nutrient medium, like oak, and a medium rich in anti-microbial extractives, like cedar, should outlast biofilter media lacking these qualities, like aspen and cobs.

Our objective was to determine the longevities of organic biofilter medium types relative to their traits in order to improve the predictability of medium service life. To do this, we utilized litter bags and characterized medium traits to measure and predict biofilter medium decay rates, adopting the approach commonly used to study decay in natural systems (Prescott 2010). By comparing medium decay in the presence of and without the N-rich ammonia emissions from livestock production which can enrich media, biofilters offered an ideal system in which to test the influence of N loading on decomposition, N being an important plant trait which can be used to predict and control decay in natural systems (Knorr et al. 2005). By correlating decay rates with medium traits, including a targeted assessment of the effect of N enrichment, we hope to enable biofilter engineers and farmers to better assess medium costs and replacement frequency trade-offs. By improving service life predictions and cost analyses through direct use or incorporation into decision-making tools, these data might facilitate expanded usage of biofilters on farms and for other uncontrolled effluents.

Materials and methods

Biofilter media, litter bags, and field site

The biofilter media tested included locally sourced softwoods (cedar, eastern red, *Juniperus virginiana*; pine, eastern white, *Pinus strobus*; SYP, southern yellow pine, *Pinus* spp.), hardwoods (ash, white, *Fraxinus americana*; aspen, quaking, *Populus tremuloides*; birch, paper, *Betula papyrifera*; maple, sugar, *Acer saccharum*; oak, northern red, *Quercus rubra*), a forestry by-product (mulch) composed of chipped tree branches and shrubs of mixed species, and an agricultural by-product (cob, maize, *Zea mays*). Sapwood tissues and by-products were processed using a disk chipper and then sieved, selecting chips in the 1–2 cm fraction (Fig. S1a–d in the Supplementary Material).

Litter bags containing media (n=40 per type) were prepared using 20 cm^2 pieces of nylon window screen (~1 mm openings) folded in half and heat-sealed on the edges. A soldering iron was used to melt a hole in the corner of each bag, and a numbered aluminum tag was affixed with a nylon cable tie. Bags were tared, 30 g of conditioned media (65 % RH, 20 °C, until mass stabilized, ~2 weeks) was added, the top of the litter bag was sealed, and the total weight was recorded (Fig. S1e in the Supplementary Material).

Litter bags were deployed in March 2012 in the northwest, up-flow, flat-bed, birch woodchip biofilter at the University of Minnesota West Central Research and Outreach Center swine nursery barn in Morris, MN, detailed in Janni et al. (2014). To test the effects of emissions on biofilter medium decay, half of the litter bags were buried in the biofilter bed treating barn emissions from a regularly running exhaust fan ("treatment" location). The other half of the litter bags were buried in a partitioned area of the biofilter where the exhaust fan was shut off and emission flow was restricted by plastic sheeting across the plenum ("control" location) (Fig. S1f–h in the Supplementary Material). Comparisons of average moisture content and inlet emissions of the two biofilter locations are summarized in Table S1 in the Supplementary Material.

At four collection times (3, 6, 15, and 27 months), five replicate bags of each medium type were collected from the treatment and control locations. Upon collection, adhering material was removed, the wet field weights were recorded, and bags were re-conditioned (65 % RH, 20 °C, until mass stabilized, ~2 weeks). Weight loss was calculated from the

difference of the initial and post-harvest conditioned weights. Using the single, first-order exponential model of decay, the decay rate constants were determined as

$$k = \frac{\ln\ (M_1/M_2)}{t} \quad (1)$$

where M_1 = mass of the sample at time = t_1 (g), M_2 = mass of sample at time = t_2 (g), t = length of decay time from t_1 to t_2 (years), and k = decay rate constant (year^{-1}). Constants were determined for the initial sample harvest (0–3-month loss), for year 1 (3–15-month loss, June 2012–2013), year 2 (15–27-month loss, June 2013–2014), and over the entire experiment (0–27-month loss).

Medium characterization

Size fractions and medium bulk density were measured by the methods of Janni et al. (2014). Dry weight was calculated from the conditioned weight knowing wood conditioned at 65 % RH and 20 °C has an equilibrium moisture content of 12.0 % (Forest Products Laboratory 2010). Media were air dried and milled to pass 40 mesh, and medium chemical analyses following the methods of Schilling et al. (2015a) were conducted. To summarize, ash content was determined gravimetrically after 24 h at 600 °C. Extractive content was determined on a dry weight basis following 24-h Soxhlet extraction in 90 % ethanol. Extractive-free powder was then hydrolyzed in 72 % H_2SO_4. Solubilized saccharides were measured using high-performance liquid chromatography while acid-soluble lignin was measured by light absorption at 320 nm for cob and 240 nm for woody substrates. The insoluble lignin was measured gravimetrically. Wood acidity (pH) was determined in a 1-mg wood powder per 0.01 mL of 5 mM $CaCl_2$ solution. Dilute alkali solubility (DAS) was also determined as an assessment of rot type (Schilling et al. 2015b). Additionally, total C and N were measured by dry combustion gas chromatography (GC) analysis on a Costech Analytical ECS 4010 equipped with a TCD detector (Costech Analytical Technologies, Inc., Valencia, CA, USA) at the Nebraska Ecosystem Analytical Laboratory. Other inorganics were measured by inductively coupled argon plasma optical emission spectrometry (ICP-OES) on an Optima 3000 ICP Spectrometer (Perkin Elmer, Waltham, MA, USA) at the University of Minnesota Research Analytical Laboratory. Three replicates were run for each medium type for each analysis. Initial characteristics are shown in Table 1.

Nitrogen treatment tests

To test the influence of N content on biofilter medium longevity, SYP and birch chips were vacuum infiltrated with an aqueous solution of organic N. Casein hydrolysate was the organic N used as its composition is similar to the protein and amino N that typifies the N forms found in wood (Nordin et al. 2001). Chips were also treated with water as a control. Target N concentrations were 0.2 % (control), 0.50 %, 0.75 % (to match N levels in mulch), and 1.25 % (to exceed these levels). Control and treatment chips were rinsed post treatment and a leach test was conducted on N-treated media, similar to the methods of Hobbie et al. (2014). Three replicate samples of each medium at each treatment level were used to measure total N (after N treatment and leaching) according to the Dumas method, using a LECO FP-528 Nitrogen Analyzer (LECO Corp., St. Joseph, MI, USA) at the University of Minnesota Research Analytical Laboratory (Fig. S2 in the Supplementary Material). Treated chips were conditioned and 20 litter bags for each medium type at each treatment level were made, as before. Ten litter bags were deployed in the treatment and the control locations of the biofilter in June 2013. Litter bags were harvested in June 2014 and decay rate constants were determined.

Statistics

To meet heteroscedasticity and normality assumptions (assessed visually and tested by Shapiro-Wilk), $\log_{10}$ transformations were applied to the trait variables: extractives, glucose, Fe, K, Mg, Mn, Na, P, and C:N, and reciprocal transformations were applied to pH, lignin, total hemicellulose, Al, C, Ca, and N. Ash, xylose, galactose, arabinose, mannose, B, Cd, Ni, and Zn were not used in the analyses as they were collinear with other predictors or would not fit a normal distribution. No transformations were required for mass loss, density, lignin:N, or moisture content.

Differences in medium type characteristics, medium type mass losses, and N treatment mass losses were compared by ANOVA with differences in means tested by Tukey HSD. Control and treatment differences were compared by t test. To identify predictors of medium decay for each litter bag harvest, medium traits and medium mass loss for each time and biofilter location were correlated as is commonly done for biogeochemistry studies (e.g., Freschet et al. 2012). To further resolve drivers of decay, a multiple-regression approach was also used. For this, variables strongly correlated to mass loss (>0.5 and <−0.5 R^2) were used as predictive variables in initial full models, and variables with the least significance (highest p value) were excluded one at a time from the model until a simplified model with all variable p values <0.05 was generated. The simplified models were then compared by F test to identify the simplest model that was statistically relevant (Motulsky and Ransnas 1987). The statistical software program R version 3.1.3 (R Core Team 2015) was used for all analyses.

Table 1 Mean and (standard deviation) of initial physiochemical traits of tested biofilter media (n=3 per analysis)

Medium type	Spp.	Physiochemical traits														
		Bulk density g cm^{-3}	pH	Ash %	Extract. %	Glucose %	Hemicell. %	Lignin %	C %	Ca ppm	K ppm	Mg ppm	N %	P ppm	C:N	Lig:N
Softwoods	Cedar	0.17	3.8	0.00	3.0	39.6	15.7	29.0	51.7	717.3	121.5	74.8	0.3	30.6	177.9	99.4
		(0.00)	(0.0)	(0.00)	(0.3)	(0.5)	(0.5)	(1.1)	(0.1)	(2.0)	(9.3)	(0.3)	(0.0)	(0.1)	(19.9)	(7.8)
	Pine	0.15	4.1	0.00	4.9	40.5	21.7	31.9	51.5	640.1	184.9	103.5	0.2	17.8	256.8	158.9
		(0.01)	(0.1)	(0.00)	(0.3)	(0.3)	(0.1)	(0.3)	(0.1)	(8.4)	(5.3)	(0.7)	(0.0)	(0.6)	(66.6)	(40.0)
	SYP	0.15	3.6	0.04	2.9	48.4	20.8	20.6	49.7	270.9	63.3	40.0	0.1	22.8	364.9	150.5
		(0.01)	(0.1)	(0.05)	(0.2)	(0.5)	(0.5)	(0.7)	(0.1)	(2.4)	(7.1)	(0.4)	(0.0)	(1.6)	(51.2)	(17.1)
Hardwoods	Ash	0.19	4.6	0.03	4.5	45.6	19.8	22.5	49.0	438.3	1535	148.3	0.2	180.8	203.3	93.1
		(0.01)	(0.0)	(0.06)	(0.2)	(0.2)	(0.3)	(1.4)	(0.1)	(11.3)	(28.9)	(5.8)	(0.0)	(4.5)	(12.2)	(1.1)
	Aspen	0.13	4.2	0.26	1.9	49.2	30.1	20.5	48.5	1105	107.1	88.9	0.2	38.0	234.2	98.4
		(0.01)	(0.0)	(0.12)	(0.5)	(0.6)	(3.2)	(1.7)	(0.1)	(4.5)	(9.7)	(0.5)	(0.1)	(3.0)	(39.3)	(9.5)
	Birch	0.17	4.2	0.00	2.0	44.0	25.4	19.0	48.7	613.4	138.8	151.1	0.2	56.3	225.6	87.6
		(0.01)	(0.0)	(0.00)	(0.5)	(0.7)	(0.3)	(1.3)	(0.1)	(3.6)	(3.8)	(0.8)	(0.0)	(0.6)	(18.0)	(1.3)
	Maple	0.17	4.5	0.25	2.0	52.0	18.3	22.0	48.6	1130	330.0	128.8	0.2	73.5	216.7	98.0
		(0.01)	(0.0)	(0.15)	(0.2)	(0.7)	(0.6)	(0.3)	(0.1)	(13.5)	(10.6)	(1.3)	(0.0)	(0.9)	(21.8)	(9.0)
	Oak	0.20	3.5	0.20	6.3	43.0	23.5	22.8	49.1	358.6	784.5	8.4	0.3	9.7	196.7	91.2
		(0.01)	(0.1)	(0.06)	(0.4)	(1.0)	(2.5)	(0.5)	(0.1)	(4.6)	(14.6)	(0.3)	(0.0)	(0.2)	(19.0)	(7.3)
By-products	Mulch	0.13	6.1	3.05	2.2	35.6	17.4	26.7	48.0	13557	3248	1015	0.8	795.3	61.6	34.3
		(0.01)	(0.1)	(0.17)	(0.3)	(0.6)	(1.2)	(1.1)	(0.2)	(402)	(31.4)	(20.1)	(0.1)	(10.4)	(3.8)	(1.0)
	Cob	0.15	4.4	0.26	5.3	38.9	39.9	18.9	47.2	202.1	5094	325.7	0.7	927.3	64.1	25.7
		(0.01)	(0.0)	(0.16)	(0.3)	(0.4)	(0.3)	(0.3)	(0.2)	(3.3)	(55.9)	(5.1)	(0.2)	(19.7)	(1.7)	(1.0)

Results

Decay rates of various biofilter media

For both the treatment and control biofilter locations, the by-product media decayed the fastest while the softwood media decayed the slowest (Figs. 1 and 2). Unlike other media, by-products lost significant mass shortly after litter bag deployment. In the first 3 months, the average mass losses in the treatment and control biofilter locations were 31.4 and 28.7 % for the mulch, respectively, and 20.1 and 11.2 % for the cob, respectively. No other media lost more than 10 % of their mass in the first 3 months (Figs. 1 and 2), though ash did have elevated first year k values in the control area (Table 2).

Average decay rates for all medium types accelerated in year 2 (Table 2). Generally, these year 2 decay rates were greater than the k values calculated for the same media using the 27-month losses. A notable exception was the mulch, which was the only medium to have a greater 27-month decay rate constant. With this slowing of mulch decay in year 2, the final remaining mass percentage of mulch was not significantly different from most of the hardwoods.

Predictors of biofilter medium longevity

Medium traits were useful predictors of medium longevity, particularly C fractions and nutrient content. In the treatment location, the top 5 predictors of 27-month decay were P (R^2=0.886), C (R^2=−0.863), K (R^2=0.785), lignin:N (R^2=−0.772), and pH (R^2=−0.742), while C (R^2=−0.930), lignin:N (R^2=−0.726), P (R^2=0.707), lignin (R^2=−0.642), and K (R^2=0.627) ranked highest for the control location (Table S2 in the Supplementary Material). Nutrient content was also a key predictor of mid- and early decay, where decay for both biofilter locations at 3, 6, and 15 months was best correlated with P (R^2>0.802) followed by other nutrient predictors (e.g., N, P, K, Mg, pH).

The multiple trait model approach also identified C fractions and nutrient variables as the best predictors of long-term decay and nutrient variables as the best predictors of early decay. For 27-month mass loss, the best predictor for both biofilter locations was C, followed by Mg and K for the treatment and C:N and hemicellulose for the control (Table 3). Both of these regressions could predict over 95 % of the 27-month medium mass loss. Over 83 % of the mass loss in the treatment and 88 % of the mass loss in the control could be explained by C and N metrics alone (Table 3). For 3-month

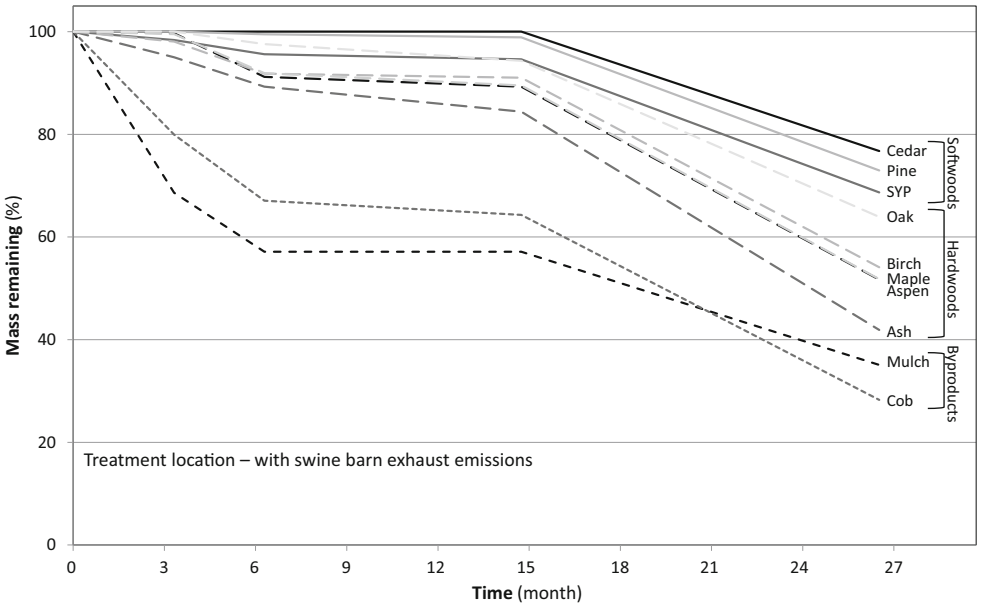

Fig. 1 Mass loss of biofilter media incubated in the treatment location (n=5)

mass loss, the best predictor for both locations was pH, followed by other metrics of medium quality (e.g., N, C:N, C) (Table 3). These regressions could explain over 96 and 88 % of 3-month mass loss in the treatment and control locations, respectively.

Effect of N loading on decay of biofilter media

Increasing the N content of birch and SYP significantly enhanced the decay of these media in both the treatment and control biofilter locations. With the birch medium, increasing the N content to approximately 1.25 % N resulted in an increase in mass loss from 29.69 to 54.85 % for the treatment location and from 25.04 to 42.29 % for the control location (Fig. 3). Even a modest N content increase to ~0.5 % N enhanced medium mass loss significantly, up to 44.85 and 37.58 % for the treatment and control locations, respectively. The k values associated with N-treated birch media were significantly higher than controls and reached values larger than those calculated for by-product media (Tables 2 and 4).

Similar, though smaller, N effects were evident for the N-treated SYP media (Fig. 4). With these media, increasing the N content to the 1.25 % N target resulted in an increase in mass loss from 24.88 to 31.68 % for the treatment location and from 5.19 to 16.20 % for the control location. At lower N

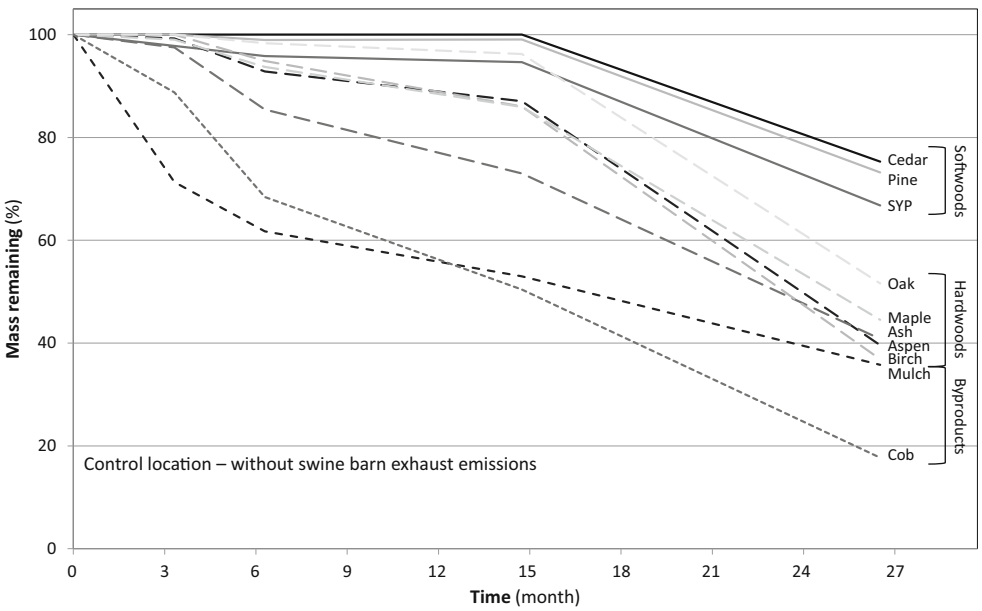

Fig. 2 Mass loss of biofilter media incubated in the control location (n=5)

Table 2 Mean and (standard deviation) of decay rate constants for the first 3 months (k_{3mo}), for losses from June 2012 to June 2013 ($k_{year\ 1}$), for losses from June 2013–2014 ($k_{year\ 2}$), and for the full 27 months of decay (k_{27mo}) for both the treatment and control biofilter locations (n=5)

Location	Medium type	Spp.	Decay rate constants							
			k_{3mo}		$k_{year\ 1}$		$k_{year\ 2}$		k_{27mo}	
			year^{-1}		year^{-1}		year^{-1}		year^{-1}	
Control	Softwoods	Cedar	−0.074	(0.004)	0.007	(0.008)	0.292	(0.006)	0.126	(0.005)
		Pine	−0.059	(0.019)	0.026	(0.007)	0.303	(0.013)	0.139	(0.005)
		SYP	0.088	(0.012)	0.034	(0.005)	0.342	(0.006)	0.180	(0.004)
	Hardwoods	Ash	0.044	(0.197)	0.306	(0.064)	0.591	(0.164)	0.405	(0.084)
		Aspen	0.006	(0.075)	0.140	(0.030)	0.791	(0.111)	0.414	(0.047)
		Birch	−0.068	(0.033)	0.170	(0.058)	0.859	(0.242)	0.450	(0.086)
		Maple	0.032	(0.044)	0.146	(0.053)	0.660	(0.141)	0.364	(0.068)
		Oak	−0.058	(0.033)	0.054	(0.006)	0.632	(0.051)	0.294	(0.023)
	By-products	Mulch	1.356	(0.189)	0.277	(0.046)	0.428	(0.468)	0.478	(0.157)
		Cob	0.486	(0.316)	0.579	(0.207)	1.044	(0.226)	0.775	(0.079)
Treatment	Softwoods	Cedar	−0.089	(0.013)	0.008	(0.016)	0.283	(0.038)	0.118	(0.009)
		Pine	−0.044	(0.019)	0.022	(0.003)	0.293	(0.028)	0.140	(0.009)
		SYP	0.065	(0.008)	0.039	(0.009)	0.319	(0.015)	0.167	(0.008)
	Hardwoods	Ash	0.205	(0.074)	0.118	(0.015)	0.700	(0.126)	0.390	(0.058)
		Aspen	0.015	(0.039)	0.110	(0.010)	0.554	(0.170)	0.298	(0.074)
		Birch	0.078	(0.045)	0.075	(0.026)	0.519	(0.068)	0.274	(0.034)
		Maple	0.021	(0.117)	0.105	(0.038)	0.555	(0.093)	0.294	(0.043)
		Oak	−0.048	(0.017)	0.071	(0.035)	0.387	(0.048)	0.199	(0.006)
	By-products	Mulch	1.509	(0.160)	0.178	(0.086)	0.503	(0.561)	0.504	(0.232)
		Cob	0.898	(0.141)	0.217	(0.068)	1.142	(0.289)	0.722	(0.127)

treatments, increased decay was also observed. The k values associated with N-treated SYP media were significantly higher than the controls and reached values as large as those for hardwood media (Tables 2 and 4).

Influence of livestock emissions on decay rates

The control location of the biofilter had significantly lower livestock emission concentrations than the treatment location.

Table 3 Significant simplified models for predicting biofilter medium weight loss for early (3 months) and long-term (27 months) decay for each biofilter location (control and treatment) noting the intercept, coefficient values, degrees of freedom (df), and the adjusted coefficient of determination (R^2). Long-term models using only C and N as predictors are also included

Dependent variable	Intercept	Predictor variables* (in order of significance from left to right)							df	R^2
Mass loss		Value of coefficient								
3 months control	4.9490	pH^{-1} −1.3310	Al^{-1} −0.2140	N^{-1} −0.0002					26	0.8833
3 months treatment	1.9988	pH^{-1} −1.2330	$\log_{10}Fe$ 0.0466	Dens −0.8301	N^{-1} −0.0062	$\log_{10}CN$ 0.0121	$\log_{10}Na$ 0.0132	C^{-1} −3.0643	22	0.9636
27 months control	5.3767	C^{-1} −9.3875	$\log_{10}CN$ −0.0004	$Hemi^{-1}$ −0.0340					26	0.9547
27 months treatment	3.5246	C^{-1} −7.0797	$\log_{10}Mg$ 0.1002	$\log_{10}K$ 0.0828					26	0.9526
27 months control	6.0960	C^{-1} −11.2000	N^{-1} −0.0002						27	0.8787
27 months treatment	5.0910	C^{-1} −9.1240	N^{-1} −0.0003						27	0.8352

*p values for all models were <0.001

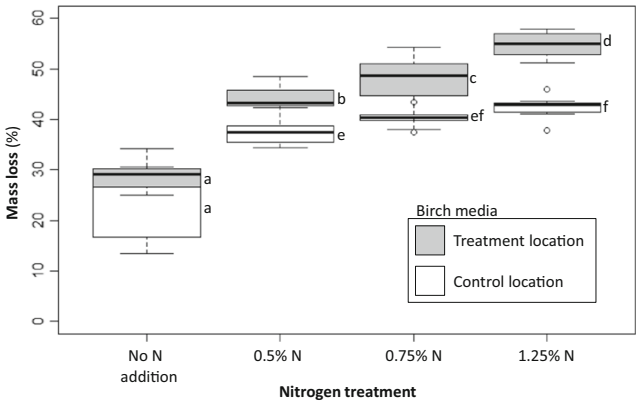

Fig. 3 Mass loss of N-amended birch media incubated in the treatment and control locations of the biofilter for 12 months (n=10). *Different letters* denote means that are significantly different (α=0.05)

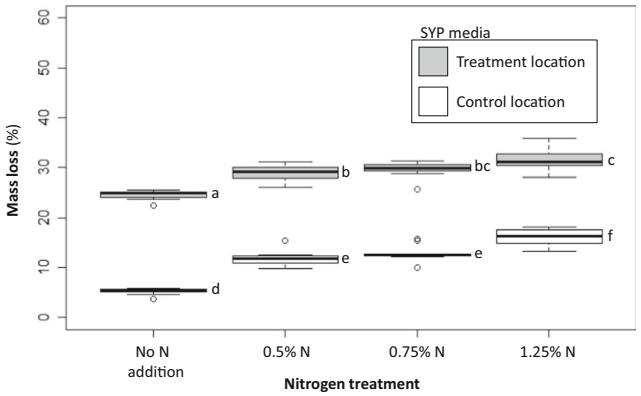

Fig. 4 Mass loss of N-amended SYP media incubated in the treatment and control locations of the biofilter for 12 months (n=10). *Different letters* denote means that are significantly different (α=0.05)

Methane, ammonia, and hydrogen sulfide concentrations were more than 3, 6, and 31 times lower in the control location, respectively (Table S2 in the Supplementary Material). No significant differences were seen with carbon dioxide, nitrous oxide, or sulfur dioxide. The treatment location was found to be slightly drier than the control location when moisture content data was pooled for all sample collections, though levels for both locations were normal for biofilter operation (Chen et al. 2009).

Differences in decay between the treatment and control biofilter locations were varied and time dependent for mixed-medium types, but stimulation of decay by emissions was evident in the N treatment experiment. With the mixed-medium types, treatment losses were slightly larger than control losses for the first collections of litter bags (Figs. 1, 2, and S3 in the Supplementary Material). These differences were only significant at 3 months for birch and cob media and at 6 months for birch and mulch media. In later collections, this pattern shifted, with slightly less decay measured for the treatment versus the control location. These differences were only significant at 15 months for ash and cob media and at 27 months for aspen, birch, and oak media. No significant difference was measured between treatment and control locations for any time collection when softwood or hardwood medium losses were collectively compared (Fig. S3 in the Supplementary Material).

In the N treatment experiment, both birch and SYP media decayed more rapidly in the presence of emissions regardless of their N content. These differences were significant in all cases except for the untreated birch control. To explore the effect of emissions on untreated media, the no N birch and SYP weight losses were compared to losses of birch and SYP media from the mixed-medium litter bag experiment (Fig. S4 in the Supplementary Material). When located in the control location, the average mass losses of the no N medium was more similar to year 1 losses, but when located in the treatment, they were more similar to the larger year 2 losses. There were also combined effects of N treatment and emissions. In the control location, the N-treated birch and SYP medium average mass losses approached the losses observed for year 2 litter bags, and for birch, there was no significant difference between the mass loss of the 1.25 % N treatment and the average mass losses for year 2. In the treatment location, the combined effect of emissions and N resulted in N-treated birch and SYP average mass losses exceeding year 2 losses. This was significant for birch and SYP at N treatments of 0.5 % and above.

Table 4 Means and (standard deviations) of decay rate constants for the N-treated birch and SYP media for both the treatment ($k_{Treatment}$) and the control ($k_{Control}$) biofilter locations

Spp.	Number	$k_{Treatment}$		$k_{Control}$	
		year^{-1}		year^{-1}	
Birch	Control	0.336	(0.029)	0.292	(0.092)
	0.5	0.591	(0.042)	0.473	(0.043)
	0.75	0.672	(0.122)	0.517	(0.028)
	1.25	0.796	(0.053)	0.552	(0.038)
SYP	Control	0.283	(0.013)	0.053	(0.007)
	0.5	0.342	(0.022)	0.125	(0.018)
	0.75	0.352	(0.022)	0.138	(0.019)
	1.25	0.378	(0.032)	0.177	(0.021)

Discussion

Medium decay patterns were distinct

Using the litter bag approach, we were successful in comparing the decay patterns of various biofilter media under full-scale operational conditions. Our results show that softwood media were the most durable, while the by-product materials decayed fastest during the 27-month trial. This was not

surprising as these patterns are typical of woody litter in natural systems. The meta-analysis by Weedon et al. (2009) covering all forested continents, for example, showed softwood *k* values routinely smaller than their hardwood counterparts. Despite this similarity in relative decay rates among medium types, decay was consistently faster in our engineered environment. Observed *k* values were roughly an order of magnitude greater than average *k* values for comparable fine and coarse woody debris in natural systems (Pietsch et al. 2014; Russell et al. 2014; Weedon et al. 2009). Decay rate constants for by-product biofilter media were also larger than those for woody mulches decayed in natural environments (Valenzuela-Solano and Crohn 2006) and corn cobs decayed in agricultural fields (Wienhold et al. 2011). In fact, when *k* values are compared, woody biofilter media degraded as quickly as mulches in natural environments while by-product biofilter media degraded as quickly as some foliar litters (Pietsch et al. 2014; Zhang et al. 2008).

It is likely that decay rates are higher in a biofilter than in a natural system because of the unique environment of the packed bed and its enrichment in ammonia-N. A biofilter is an engineered system designed and managed for optimal microbial activity and performance (Mudliar et al. 2010). Biofilter media are selected both to promote airflow and to stimulate diverse microbial biofilms, with water content (Schmidt et al. 2004) and sometimes pH (Vaiškūnaitė and Navickaitė 2011) actively managed to support these growths. The tempered effluents with diverse emissions further stimulate these microbial growths (Cabrol and Malhautier 2011), and ammonia-N enrichment of the C-rich woody substrates can decrease C:N and enhance medium breakdown by biofilter microbes.

Decay rates can also differ between environments (i.e., biofilter and natural) due to medium size and differences in the decay rate calculation method (Harmon et al. 2000). Regarding medium size, it is reasonable to assume that our chipped media may be small and of a higher surface area to volume ratio than woody debris of a forest, and this difference could contribute to elevated decay rates of biofilter media. Our biofilter medium *k* values still often exceeded published *k* values for smaller twigs and fine woody debris (Berbeco et al. 2012; Fasth et al. 2011), suggesting size differences may not explain the differences in rates. For the calculation method, we assumed negative exponential decomposition. While this is the most commonly used approach, short studies can result in inflated *k* values due to the changes in decay rates over time (Cornwell and Weedon 2014; Harmon et al. 2000). Though our study was relatively short in duration (Russell et al. 2014), 27 months nears the half-life of most biofilter media (Chen et al. 2009) and the weight losses we report for biofilter media at 27 months are similar to weight losses reported after 5 years of decay in natural systems. It is also unlikely that our media has reached an asymptote of decay, as outlined by Harmon et al. (2000), or that decay would stall for several years. It seems reasonable therefore that biofilter media decay more rapidly and that calculation of higher *k* values is not an artifact of study length.

When biofilter medium *k* values were calculated for different fractions of the decay period, clear differences between initial, year 1, and year 2 rates were observed. Unlike natural and urban systems where the rate of decay progressively diminishes for most tree litters (Cornwell and Weedon 2014; Hobbie et al. 2014), the decay rate for most biofilter media seemed to increase with time. Only mulch, cob, and, to some degree, ash showed the expected rapid phase of early decay, but even with these media, their *k* values for year 2 exceeded or were not significantly different than initial rates. An initial lag time in decay for some wood types has been attributed to slow colonization by decomposing organisms (Harmon et al. 2000). It is recognized in forest systems that there are transitions from an endemic decay community in wood to more dominant decay organisms (Boddy and Heilmann-Clausen 2008) and that the rate of this shift is dependent on the organisms involved, litter conditions, and the environment (Hiscox et al. 2015). Temporal changes in biofilter communities are likely to be governed by similar principles (Cabrol and Malhautier 2011), and though this work did not explore biofilter microbial communities, perhaps the selective pressure of the unique biofilter environment slowed the initial colonization of media by robust decay organisms but then stimulated their growth following colonization.

Medium quality predicted decay

Though the patterns of decay showed some deviation from natural systems, the predictors of decay for biofilter media were familiar. Our correlations showed decay rates increased with nutrient levels (N, P, K, Ca, and Mg) and decreased with recalcitrant fractions (C and lignin). These variables, which were highly effective at predicting biofilter medium decay, are regular components of models developed for decay predictions in natural systems (Prescott 2010). Similar to the work of Zhang et al. (2008), which identified lignin:N as the key predictor of long-term decay, our work found recalcitrant fractions (C and lignin), nutrients, and their ratio (i.e., lignin:N) were highly predictive of biofilter medium longevities.

As decay was initiating, recalcitrant fractions were less important and nutrient content was the key predictor. As decay progressed, the role of C and lignin emerged as a better predictor. A similar shift in predictors of early and long-term decay is typical in natural systems (Prescott et al. 2004). It is interesting to note that while P was the most tightly correlated to early biofilter mass loss, it was not a significant variable in the regressions, seemingly replaced by pH. While pH does correlate with P (Table S2 in the Supplementary Material), and may be indicative of base cation content, its role in decay

can vary depending on the substrates tested (Freschet et al. 2012; Schilling et al. 2015a). Nitrogen was another prominent nutrient predictor, in early decay as N and over longer decay periods as C:N. Though the significant models included additional quality variables, simple regressions using only C and N could effectively predict medium mass losses.

It is important to note that other predictors of decay that were not measured here, such as microbial community functional indexes, may also have predictive capacity. Different microbial communities are known to degrade certain plant tissues and types (Veen et al. 2015), and DAS values in this study do suggest different rot types for different medium types (Table S3 in the Supplementary Material). While many organic materials can work as biofilter media, it would be of interest to see if a decay-resistant medium, like cedar, also limits the growth of microbial biofilms essential for biofilter function. Discerning the microbial community, and more importantly its role, is a difficult task (Cabrol and Malhautier 2011), however, and would be beyond the capabilities of most biofilter end-users. The adequate predictors of C and N, on the other hand, are familiar to most livestock producers and laboratory services are already in place for their analyses. These services and our models provide end-users with a means to choose between two outwardly similar mixed media (i.e., mulches) and identify the one likely to provide the best longevity.

N enrichment altered decay rates

With N a predictor of decay for both early and late stages, it is without surprise that by increasing the N content of soft- and hardwood chips, decay significantly increased. Our findings also provide some evidence that livestock emissions rich in N can alter decay rates. Though varied effects of biofilter location were observed for the mixed-medium types, the decay of SYP and birch litter bags with and without N treatment was significantly higher in the treatment location. The stimulatory effect of medium N concentrations on the birch medium appeared more significant with the emission enrichment, while the effect was smaller for the lower quality SYP medium despite higher N retention in the medium. Nitrogen stimulation of decay is known to depend on litter quality, with a stronger stimulation for high-quality (i.e., low-lignin, high-nutrient) litters (Knorr et al. 2005). Our characterization work showed the birch medium to be of somewhat higher quality than the SYP medium (Table 1), explaining in part the variable effect. Although birch had a larger response to the N treatment, SYP had a larger response to enrichment from the effluent, regardless of N content. It is likely that the interactions of litter quality, N form, and decay communities all collectively impact biofilter medium decay rates, as well as biofilter performance. Here, we provide some evidence for these processes and highlight the potential of the litter bag technique to further explore these dynamics in the unique biofilter system.

Recommendations for biofilter end-users

Although biofilters offer a low-cost pollution control technology compared to other mitigation options for farm emissions (Delhomenie and Heitz 2005), costs can still be >$1000 m^{-3} (van Lith et al. 1997) with sizing dependent on effluent volume and emission flow rates (Schmidt et al. 2004). Media may not be as significant a construction cost as ducting and labor, but costs can still be significant, ranging from $0 to $25 m^{-3} for by-products, $20 to $40 m^{-3} for woodchips (based on regional quotes), and $100 to over $300 m^{-3} for engineered media (van Lith et al. 1997; Dorado et al. 2010a). While many biofilter medium types have been shown to be effective at mitigating livestock production emissions, including various soft- and hardwoods (Akdeniz et al. 2011; Janni et al. 2014), wood mulch is most commonly used (Chen et al. 2009). Agricultural by-products have promise as a future medium type and might be readily available, low-cost, and functional medium types (Akdeniz et al. 2014; Ramirez-Lopez et al. 2003), but our work suggests they might also require more frequent replacement. With additional quantification of medium decay rates, however, medium longevities and cost trade-offs can be properly assessed.

To provide an example of applying our data, we can set a reasonable lifespan for a mulch biofilter at 3 years and use the calculated decay rate constant of 0.504 and the exponential decay model to find 22.1 % of the mass remains at the time the media is exhausted. Using this level of decay as a threshold, we can estimate softwood media to last 10.7 years, hardwood media to last 5.2 years, and cob media to last 2.1 years. If we apply these values to an example swine barn biofilter system (ventilation rate of 30,000 cfm, empty bed contact time of 5 s, required medium volume of 70 m^3 based on biofilter design guidelines of Schmidt et al. (2004)), we can then compare costs. Estimating medium costs ($35 m^{-3} softwood, $30 m^{-3} hardwood, $25 m^{-3} mulch, $15 m^{-3} cobs) and delivery charge (set at $250, but will vary from on-farm vs. off-farm), the replacement costs would be $2,700, $2,350, $2,000, and $1,300 for softwood, hardwood, mulch, and cob media, respectively. If, however, we divide by longevity in order to factor replacement frequency, the annual costs shift to $252, $452, $667, and $619 for softwood, hardwood, mulch, and cob media, respectively. This would effectively make the most expensive media to replace (softwood chips) the best overall value. When one considers farms typically have many barns, these differences in annual cost can become quite significant. In any case, this must be placed in context with varying delivery charges, performance attributes, medium costs, and availability, but the example demonstrates the potential to integrate

these decay data to support end-user decision-making tools, e.g., Feedlot Air Emissions Treatment Cost Calculator (Lazarus 2013), and potentially hasten adoption of this promising technology.

In this work, medium degradation was assessed as weight loss, though the ability of media to resist breakdown into fine particles and thus resist compaction, gas channeling, and pressure drop is also important. It is noteworthy that while cob media had significant mass loss, the cob pieces were slow to break down into fine particle sizes (Fig. S5 in the Supplementary Material). Cobs, however, with their "sponge-like" physical properties and easily degradable sugar content, were also found to have high water holding capacities and extensive biofilm growths. These properties have been associated with increased bed compaction (Dorado et al. 2010b) and may negate the benefits of reduced fragmentation. Additional tests will be needed to more closely explore these dynamics. Here, we provide an extensive survey of decay rates in widely used medium types that, as stand-alone comparisons, offer practical information to end-users of any bioreactor technology. We show that biofilter medium decay patterns are similar to those in natural systems and have familiar biogeochemical controls that are useful as predictors of medium breakdown. With this knowledge, we enable biofilter engineers and farmers to quantitatively assess medium longevity and cost trade-offs. We hope this data can be incorporated into decision-making tools, to clarify actual operational costs, improve selection of media, and ultimately facilitate the increased usage of biofilters for livestock production emissions.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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