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Leaf litter density and decomposition in small man-made ponds

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Abstract:	<p>The input of terrestrial leaf litter into aquatic ecosystems supports aquatic food webs and fuels microbial metabolism. Although the role of leaf litter subsidies to streams have been studied extensively the effect of leaf litter in lentic systems has received less attention. In particular the impact of leaf litter on the ecology and biogeochemistry of small man-made ponds is virtually unknown, despite the fact that these systems are extremely common and likely represent a substantial modification to watersheds in the North America. We measured the areal density of leaf litter and the rate of leaf litter decomposition in small man-made ponds in central Virginia to determine the size of the leaf litter pool in these systems, the rate at which leaf litter is decomposed, and the extent to which pond characteristics alter leaf litter abundance or processing. We found that the areal density of leaf litter in the ponds ranged between 3.4 and 1179.0 g AFDM m⁻². The areal density of leaf litter was significantly greater in the littoral zones of the ponds, however leaf litter was present in the sediments throughout the pond. There was no relationship between the areal density of leaf litter in the sediments and the percent organic matter of the fine sediments, suggesting that leaf litter input is decoupled from bulk sediment organic matter. The decomposition rate of <i>Liriodendron tulipifera</i> leaves in coarse mesh leaf packs ranged between 0.0025 and 0.0035 d⁻¹, which is among the slowest litter decomposition rates recorded in the literature for ponds and was unrelated to pond characteristics. Our results indicate that leaf litter is an abundant and persistent pool of organic matter in the sediments of small man-made ponds and it is likely to have a substantial effect on the trophic dynamics and biogeochemistry of these systems.</p>
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Dear Editor,

Please consider our manuscript “Leaf litter density and decomposition in small man-made ponds” for publication in Freshwater science. Our paper shows how small man-made ponds accumulate and retain leaf litter from their watersheds. We show that these ponds have some of the lowest reported rates of leaf litter decomposition and that the ponds have a high density of leaf litter in their sediments. Given the abundance of small man-made ponds, we feel that quantification of the dynamics of leaf litter processing in these systems is essential to understanding how humans are altering watershed organic matter cycling.

None of the data, text, or figures have been used in any other publications and we agree to pay all page charges associated with the publication of our manuscript.

Thank you for considering our manuscript for publication and we look forward to your feedback.

Sincerely

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1 **Leaf litter density and decomposition in small man-made**
2 **ponds**

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5 **Abstract**

6 The input of terrestrial leaf litter into aquatic ecosystems supports aquatic food webs and fuels
7 microbial metabolism. Although the role of leaf litter subsidies to streams have been studied
8 extensively the effect of leaf litter in lentic systems has received less attention. In particular the
9 impact of leaf litter on the ecology and biogeochemistry of small man-made ponds is virtually
10 unknown, despite the fact that these systems are extremely common and likely represent a
11 substantial modification to watersheds in the North America. We measured the areal density of leaf
12 litter and the rate of leaf litter decomposition in small man-made ponds in central Virginia to
13 determine the size of the leaf litter pool in these systems, the rate at which leaf litter is decomposed,
14 and the extent to which pond characteristics alter leaf litter abundance or processing. We found that
15 the areal density of leaf litter in the ponds ranged between 0.00334 and 1.179 kg AFDM m⁻². The
16 areal density of leaf litter was significantly greater in the littoral zones of the ponds, however leaf
17 litter was present in the sediments throughout the pond. There was no relationship between the
18 areal density of leaf litter in the sediments and the percent organic matter of the fine sediments,
19 suggesting that leaf litter input is decoupled from bulk sediment organic matter. The decomposition
20 rate of *Liriodendron tulipifera* leaves in coarse mesh leaf packs ranged between 0.0025 and 0.0035 d⁻¹,
21 which is among the slowest litter decomposition rates recorded in the literature for ponds and was
22 unrelated to pond characteristics. Our results indicate that leaf litter is an abundant and persistent
23 pool of organic matter in the sediments of small man-made ponds and it is likely to have a
24 substantial effect on the trophic dynamics and biogeochemistry of these systems.

25 **Introduction**

26 Ecosystem subsidies, the movement of resources across ecosystem boundaries
27 (Polis et al. 1997), are an important part of organic matter cycling in aquatic
28 systems. The reciprocal transfer of resources between aquatic and terrestrial

systems is common (Nakano and Murakami 2001; Baxter et al. 2005) , however the input of terrestrial organic matter to aquatic systems is an especially significant flux of material since, this subsidy has been shown to support metabolism and secondary production in a majority of lentic and lotic ecosystems (Marcarelli et al. 2011). Organic matter subsidies from terrestrial to aquatic ecosystems are dominated by detrital plant material either as dissolved or particulate organic carbon, and can substantially augment autochthonous organic matter production (Hodkinson 1975; Gasith and Hosier 1976; Wetzel 1984; Wetzel 1995; Webster and Meyer 1997; Kobayashi et al. 2011; Mehring et al. 2014). Seasonal leaf fall dominates the particulate organic carbon input into most temperate aquatic systems (Wallace et al. 1999) and this detrital material serves to stabilize aquatic metabolism (Wetzel 1984).

The effects of terrestrial leaf litter subsidies on aquatic systems have received the most attention in small lotic systems (Webster and Benfield 1986). In these systems, leaf litter mass is broken down by a combination of physical and biological processes, including chemical leaching, physical abrasion, microbial mineralization, and consumption by shredding macroinvertebrates (Gessner et al. 1999). Under undisturbed conditions, leaf mass loss begins with leaching, which is then followed by conditioning of leaf material by microbial consumers, and finally consumption by shredding macroinvertebrates (Cummins 1974). Shredders can have a particularly large impact on leaf breakdown rate and leaf litter may contribute substantial material to stream secondary production (Wallace 1997; Graça 2001; Eggert and Wallace 2003; Creed et al. 2009). Anthropogenic modifications to watersheds

associated with agricultural and urban land use do not consistently change leaf litter processing rates in the stream channel (Bird and Kaushik 1992; Huryn et al. 2002; Walsh et al. 2005; Hagen et al. 2006) but can have profound impacts on the mechanisms of leaf breakdown (Bird and Kaushik 1992; Paul et al. 2006; Imberger et al. 2008) and thus alter the impact of detrital subsidies.

Small impoundments (i.e., man-made ponds) are a common anthropogenic alteration to watersheds in the United States (Downing et al. 2006; Downing 2010), but their impact on leaf litter processing has received limited study. Impoundments have been shown to alter litter processing rates downstream of dams (Short and Ward 1980; Mendoza-Lera et al. 2010; Tornwall and Creed 2016), but estimates of litter processing within man-made ponds is limited (Table 1). Impoundment dramatically alters the physical, chemical, and biological characteristics of the system. Not only does the dam virtually eliminate flow within the created pond or lake, but temperate ponds typically stratify, producing heterogeneity in oxygen, and other dissolved components (Wetzel 2001). Further, the reduction in flow produces a depositional environment within the pond favoring the accumulation of soft sediments (Wetzel 2001). These changes to the chemical and physical environment of the pond result in substantial differences in the composition of the pelagic and benthic communities between the pond and the former lotic system (Ogbeibu 2002). Given that physical factors, and consumers (microbial and animal) are central to leaf decomposition, it is likely that man-made ponds differ substantially from surrounding lotic habitats with respect to leaf litter processing.

The abundance of the smallest ponds (< 10 ha) is more than 2 orders of magnitude greater than even modest sized lakes (100 ha), and the number of small man-made ponds is approaching the number of natural ponds (Downing 2010), indicating that small man-made ponds represent an potentially important but understudied alteration to aquatic organic matter cycling.

Our objectives for this study were to quantify the abundance of leaf litter and leaf litter decomposition rate in small ponds in a moderately urbanized region of central Virginia. We hypothesized that the ponds would contain abundant leaf litter and that leaf mass loss would be slow relative to rates typical for lotic systems. We further hypothesized that since, leaf litter decomposition is affected by temperature, nutrient availability, invertebrate community composition, and temperature (Webster and Benfield 1986) and these factors may be affected by the design and construction of man-made ponds ponds, that man-made ponds, even when geographically close, might differ substantially in leaf processing rate.

Table 1. Summary of lentic decomposition coefficients.

Source	System	Region	Litter	Mesh Size (cm)	k (d ⁻¹)
Alonso et al. 2010	small man- made lake	central Spain	<i>Ailanthus</i> <i>altissima</i>	0.5	0.008
Alonso et al. 2010	small man- made lake	central Spain	<i>Robinia</i> <i>pseudoacacia</i>	0.5	0.005

Alonso et al. 2010	small man- made lake	central Spain	<i>Fraxinus</i> <i>angustifolia</i>	0.5	0.009
Alonso et al. 2010	small man- made lake	central Spain	<i>Ulmus minor</i>	0.5	0.008
Bottollier- Curtet et al. 2011	small floodplain pond	France	mixed exotic species	1	0.0060 – 0.0575
Bottollier- Curtet et al. 2011	small floodplain pond	France	mixed native species	1	0.0066 – 0.0463
Gonçalves et al. 2004	brackish lagoon	Rio de Janeiro State, Brazil	<i>Nymphaea</i> <i>ampla</i>	0.6	4.37
Gonçalves et al. 2004	brackish lagoon	Rio de Janeiro State, Brazil	<i>Typha</i> <i>domingensis</i>	0.6	0.17
Hodkinson 1975a	abandoned beaver pond	Alberta, Canada	<i>Salix</i>	0.35	0.0027
Hodkinson 1975a	abandoned beaver pond	Alberta, Canada	<i>Deschampsia</i>	0.35	0.0018
Hodkinson	abandoned	Alberta,	<i>Juncus</i>	0.35	0.0011

1975a	beaver pond	Canada			
Hodkinson	abandoned	Alberta,	<i>Pinus</i>	0.35	0.0006
1975a	beaver pond	Canada			
Oertli 1993	small man-made pond	Switzerland	<i>Quercus robur</i>	0.5 and 1.25 (data combined)	0.0014
Reed 1979	small natural lake	Ohio, USA	<i>Acer rubrum</i>	0.30	0.015 – 0.03
This study	small man-made ponds	Virginia, USA	<i>Liriodendron tulipifera</i>	0.4	0.0025 – 0.0035

Methods

Study Site

All of the ponds used in the study are located in central Virginia and are small man-made ponds (Table 2).

The ponds used for the quantification of leaf litter areal density and sediment organic matter content were Lancer Park Pond, Daulton Pond, Woodland Court Pond, and Wilck's Lake. Lancer Park Pond is an in-line pond with an earth dam and a permanent inlet. The pond is almost completely surrounded by second growth forest. Daulton Pond is a headwater pond with a earth dam that does not have a

permanent inlet and is likely partially spring-fed. The riparian zone of Daulton Pond is approximately 50% second growth forest and 50% mowed grass. The littoral zone of Daulton Pond is mostly covered in an unidentified reed and cattails (*Typha sp.*). Woodland Court Pond is created by an earth dam that is drained by a stand-pipe. The pond has a permanent inlet and a riparian zone that is about 30% second growth forest. The remaining portion of the riparian zone is minimally landscaped disturbed land associated with an apartment complex. Approximately 50% of the littoral zone of Woodland Court Pond is a patch of cattail (*Typha sp.*). Wilck's Lake is the largest pond in the study and was created as a borrow pit for the construction of a railroad. Wilck's Lake has no obvious inlet but is drained by a stand pipe into a permanent outlet. Wilck's Lake is part of a city park and approximately 90% of the lake shoreline is second growth forest and the remaining area is mowed grass.

The ponds used to determine litter decomposition rate were Lancer Park Pond, Daulton Pond, and Campus Pond. Lancer Park Pond and Daulton Pond are described above. Campus Pond is a stormwater retention pond with a permanent inlet that is drained by a stand-pipe and is surrounded by landscaping that consists of small trees and mowed grass. Campus Pond is enclosed by an approximately 1 m tall, vertical concrete wall, so it has no natural littoral zone and is nearly uniform in depth.

Table 2. Descriptions of the ponds used in the study. Max. Z is the maximum depth recorded in the pond. Surface Area is calculated using the digitized outline of the pond in google maps with an online tool that calculates surface areas

120 (<https://www.daftlogic.com/projects-google-maps-area-calculator-tool.htm>). The
 121 latitude and longitude (Lat,Long) of the pond was measured at the approximate
 122 center of the pond using the "Whats here?" feature of google maps
 123 (<https://www.google.com/maps/>). Secchi Z is a representative Secchi depth recorded
 124 during the growing season. Chl a is a representative chlorophyll a concentration
 125 measured from the surface water during the growing season. Days Incubated is a list
 126 of the days the litter bags were in the water before being retrieved for those ponds
 127 used in the litter decomposition experiment. Chlorophyll a was not measured in
 128 Woodland Court Pond or Wilck's Lake.

Pond			Lat,Long (DD)	Secchi Z (m)	Chl a	Days Incubated
	Max Z (m)	Surface Area (ha)			($\mu\text{g L}^{-1}$)	
Campus Pond	0.5	0.07	37.297, - 78.398	0.2	40.74	0, 3, 7, 15, 21, 28, 42, 57, 82, 105, 127, 209
Daulton Pond	3.4	0.55	37.283, - 78.388	1.75	6.62	0, 3, 10, 15, 22, 30, 43, 60, 106, 128, 211
Lancer Park Pond	1.5	0.10	37.306, - 78.404	0.5	12.00	0, 2, 10, 18, 23, 37, 53, 100, 116, 204
Woodland	2.0	0.30	37.284, -	0.8	-	NA

Court Pond			78.392			
Wilck's Lake	2.0	13.18	37.304, -	0.6	-	NA
			78.415			

129 Leaf Litter Density and Sediment Organic Matter

130 To estimate the areal density of leaf litter in the ponds we used an Ekman dredge to
131 collect sediment samples from the littoral and open water regions of each pond. We
132 collected 2 replicate samples from 3 representative locations in both the littoral
133 zone and open water portions for Daulton Pond, Woodland Court Pond, and Wilck's
134 Lake on 13 May 2013, 14 May 2013, and 14 June 2013 respectively. We collected 3
135 replicate samples each from a single littoral and a single open water location in
136 Lancer Park Pond on 20 March 2013. Finally we collected a single sample from 3
137 littoral locations and 6 open water locations in Wilck's Lake on 20 February 2013. In
138 all lakes except Wilck's Lake littoral samples were collected approximately 5 – 10 m
139 from the shoreline but the actual distance was not recorded. In Wilck's Lake, dense
140 overhanging vegetation along the shoreline prevented sampling and so littoral
141 samples were collected between 10 – 20 m from the shore. The open water samples
142 were collected close to the center of the ponds.

143 The contents of the Ekman was homogenized in a plastic basin and a 10 ml sample
144 of the fine sediments was collected with a 30 ml plastic syringe with its tip cut off
145 (opening diameter = 1 cm). This sediment slurry was then placed in a pre-weighed
146 20 ml glass scintillation vial and dried at 50° C for at least 24 h. The remaining

material in the basin was sieved through a 250 μm mesh in the field and the material retained by the sieve was preserved in 70% ethanol and transported back to the lab. In the lab the preserved material was passed through a 1 mm sieve and macroinvertebrates were removed. All remaining material retained by the sieve was dried at 50° C for 48 h and homogenized with a mortar and pestle. The dried fine sediments and a subsample of the homogenized leaf litter were each ashed at 550° C for 4 h to determine the proportion of organic matter in the sample via loss on ignition (LOI). To calculate the ash-free-dry-mass (AFDM) of the total leaf litter of the sample the total dry mass was multiplied by the proportion of organic matter in the sample. The areal density of leaf litter in the pond was then estimated by normalizing the AFDM of the leaf litter to a square meter. We did not estimate the areal mass of organic matter in the fine sediments because we did not have the total dry mass of the sediments collected by the Ekman dredge.

Leaf Litter Decomposition

To determine the leaf litter decomposition rate in the ponds we measured the mass loss rate of tulip poplar (*Liriodendron tulipifera*) leaf packs. Tulip poplar was chosen for the litter species because it is common in the riparian zone of all of the ponds in the study (K. Fortino, pers. obs.). The litter was collected by gently pulling senescent leaves from the tree. Only leaves that released without resistance were used. The leaves were all collected and air-dried during the fall of 2013. The leaf packs were assembled by placing 5.0 g of intact leaves into plastic produce bags with approximately 9 mm² mesh. The bags were sealed with a zip-tie, attached to a small

bag of rocks that served as an anchor, and placed into the littoral zone of Campus Pond and Daulton Pond on 22 October 2013 and into the littoral zone of Lancer Park Pond on 29 October 2013. To determine the mass lost due to handling and deployment, 5 bags were immediately harvested following deployment at each site. Bags were harvested by gently moving the bag into a 250 μ m mesh net underwater and then gently lifting from the pond. The bag and any material retained in the net were then placed into a 11.4 L resealable plastic bag and returned to the lab. The contents of the bag was gently rinsed over a 1 mm mesh sieve to remove macroinvertebrates and then placed into a pre-weighed paper bag and dried at 50° C for at least 48 h. The dried leaf material was then weighed and homogenized with a mortar and pestle. This homogenized material was then ashed at 550° C to determine the AFDM of the leaves. The number of days that the remaining leaves were incubated in each pond is shown in Table 2.

Statistical Analysis

Differences in areal leaf litter density among ponds and between the littoral and open water zones of all ponds was determined using ANOVA. The leaf litter density was natural log transformed to homogenize the variance in the test of pond differences and for the test between the littoral and open water samples. Specific differences among ponds were assessed with a Tukey HSD post-hoc test. The relationship between areal leaf litter density and the percent organic matter of the sediments was assessed using linear regression.

The decay coefficient (k) for the leaves in the litter bags in each pond were determined by calculating the slope of the relationship between the natural log of the percent leaf mass remaining by the number of days in the pond (Benfield 2007). All statistical analysis was performed using R (R Core Team 2014).

Results

Leaf Litter Density and Sediment Organic Matter

The areal density of leaf litter in the ponds ranged between 0.00344 and 1.179 kg AFDM m^{-2} . The greatest areal leaf litter densities were found in Daulton Pond and Lancer Park Pond but in both cases the greatest areal densities were rather exceptional values (Fig. 1). The total areal leaf litter density (i.e., littoral and open water combined) differed significantly among the ponds ($F_{3, 38} = 3.955$, $p = 0.015$). The greatest areal leaf litter density was found in Lancer Park Pond with a mean (± 1 SD) density of 0.399 (± 0.436) kg AFDM m^{-2} . However the areal leaf litter density of Lancer Park Pond was only significantly different from Woodland Court pond which had a mean (± 1 SD) areal density of 0.036 (± 0.055) kg AFDM m^{-2} . The mean (± 1 SD) areal leaf litter density of Daulton Pond and Wilck's Lake were 0.175 (± 0.344) and 0.148 (± 0.194) kg AFDM m^{-2}), respectively and were not significantly different than each other or the other ponds.

In all the ponds, the greatest areal leaf litter densities were found in the littoral portion of the pond (Fig 1). Across all the ponds areal leaf litter density of the littoral

portions of the ponds ranged between 0.0097 and 1.179 kg AFDM m⁻² with a mean (± 1 SD) areal density of 0.283 (± 0.347) kg AFDM m⁻², which is significantly greater ($F_{1,40} = 28$, $p < 0.0001$) and much more variable than the areal leaf litter density of the open areas of the ponds, which ranged between 0.0034 and 0.215, with a mean (± 1 SD) density of 0.030 (± 0.0479) kg AFDM m⁻² (Fig. 1).

The percent sediment organic matter of the ponds averaged (± 1 SD) 10.3 (± 0.055)% across all ponds and ranged between a low of 0.73% in Wilck's lake and a high of 22.3% in Daulton Pond. The mean (± 1 SD) percent sediment organic matter of Wilck's Lake was 6.17 (± 3.65)%, which was significantly lower than any of the other ponds ($F_{3,37} = 6.664$, $p = 0.001$). The percent sediment organic matter of the sediments of Lancer Park Pond and Woodland Court pond were more homogeneous, but not significantly different from the sediments of Daulton Pond (Fig. 2). In all of the ponds, there was no significant difference between the open and littoral sections of the pond ($F_{1,39} = 0.963$, $p = 0.333$), nor was there a relationship between percent sediment organic matter and the density of leaf litter ($r^2 = 0.0046$, $p = 0.714$)(Fig. 2).

Litter Decomposition Rate

Litter bags were deployed in Daulton Pond, Campus Pond, and Lancer Park Pond for 211, 209, and 204 days respectively. At the end of these incubations the mean (± 1 SD) percent of the original 5 g of leaf mass remaining in Daulton Pond, Campus Pond, and Lancer Park Pond was 45.3 % (± 4.7 %), 42.3 % (± 8.2 %), 43.2 % (± 8.3 %), respectively. The three ponds had similar decay coefficients (k) but Daulton

Pond had the lowest rate at 0.0025 d^{-1} , followed by Campus pond and Lancer Park Pond with rates of 0.0030 and 0.0035 d^{-1} , respectively. All of the litter bags had been colonized by invertebrates but these were not collected quantitatively.

Discussion

Our results show that small man-made ponds collect and retain substantial amounts of terrestrial leaf litter and are therefore likely to alter organic matter processing and specifically serve as an organic matter sink within watersheds where they occur.

The areal leaf litter densities measured in the man-made ponds in this study support the observations of other authors that terrestrial detritus represents an important subsidy to lentic systems (Hodkinson 1975b; Gasith and Hosier 1976; Richey et al. 1978; Marcarelli et al. 2011). All of the ponds sampled had measurable leaf litter in their sediments. We are not aware of any other studies that measure leaf litter density in the sediments of man-made ponds in the same size class as we studied, so it is not clear how representative our measurements are of the leaf litter density of small man-made ponds globally. The only other lentic system for which we were able to find a measure of leaf litter density was for an intermittent swamp (Mehring et al. 2014). In this study the authors report that leaf litter densities range between 1080 g m^{-2} following autumn leaf fall to 578 g m^{-2} in the summer (Mehring et al. 2014), which is greater than all but the highest littoral values in the ponds we sampled. Although we did not measure the flux of leaf material to the pond,

comparisons between the densities we observed and measures of leaf litter inputs also serve to contextualize our observations. Gasith and Hasler (1976) report an input of $1.64 \text{ g m}^{-2} \text{ d}^{-1}$ of leaf litter into the littoral zone of a Wisconsin lake. In a forested mountain lake, Rau (1976) recorded a much lower deposition rate of $0.173 \text{ g m}^{-2} \text{ d}^{-1}$ and France and Peters (1995) measured an even lower leaf litter flux of approximately 0.04 and $0.02 \text{ g m}^{-2} \text{ d}^{-1}$ for the littoral zone of 4 lakes in Ontario. The magnitude of these fluxes would not be able to supply the leaf litter densities that we observed in the ponds in our study unless the litter was accumulating over many years. Our litter decomposition rates indicate that 95% of leaf litter mass would be mineralized in between 786 and 1065 days, which indicates that the litter does not persist in these systems for sufficient time for such low deposition rates to be likely. A more likely explanation is that the flux of leaf litter into the ponds in our study is greater than what has been measured in high latitude lakes but not as high as those recorded in the swamp by (Mehring et al. 2014).

The greater density of leaf litter in the littoral samples also confirms the findings of other authors that leaf litter accumulates predominantly near the shoreline (Gasith and Hosier 1976; Rau 1976; France and Peters 1995). Unlike other studies of larger systems (Rau 1976; France and Peters 1995) however, we found measurable leaf litter in the center of the pond. Gasith and Hasler (1976) hypothesize that leaf litter that enters the lake floats for a period of time before being blown toward the shore and sinking. The presence of measurable leaf litter in the offshore sediments of the lakes in our study may be due to the small surface area of our ponds, which would be insufficiently exposed to wind to exclude floating leaf litter from the open water.

276 This speculation is supported by the observation that the smallest lake in the
277 sample (Lancer Park Pond) had the most leaf litter in the offshore samples, however
278 the remaining lakes all have a similar amount of offshore leaf litter despite size
279 differences.

280 The degree to which sediment leaf litter derives from stream inputs in these ponds
281 is unknown but the significance of stream litter inputs is likely a function of stream
282 discharge, litter load, and pond volume. Lancer Park Pond, and Woodland Court
283 Ponds both have permanent first-order stream inlets, which likely serve as a
284 substantial source of litter, especially during high discharge events. Rau (1976)
285 found that litter inputs from intermittent streams around a mountain lake were
286 minor but the system in that study is not likely to be representative of the ponds in
287 our study. Although we know of no other estimation of stream leaf litter input to
288 ponds, the capacity of small streams to transport leaf litter is well known (Bilby and
289 Likens 1980). Despite the mechanisms involved, the presence of leaf litter in the
290 open water sediments of these small ponds indicates that the impact of leaf litter on
291 nutrient cycling and food-web processes extends beyond the littoral zone of small
292 ponds.

293 The degree of variability in leaf litter density within a pond was affected by the
294 location in the pond. The samples from littoral sediments were much more variable
295 than those from the open water sediments. The variability of the leaf litter density in
296 the littoral samples within each pond suggests that the factors affecting leaf litter
297 accumulation in the sediments are heterogeneous within a lake. Some of this

variation appears to be due to variation in riparian vegetation. France and Peters (1995) found that riparian vegetation affected litter fall and that litter deposition increased with the height, girth, and density of riparian trees. Rau (1976) reported greater litter deposition along forested shorelines, relative to meadow and talus in a mountain lake. In our study, the samples with the highest littoral leaf litter density were from in Daulton Pond and Lancer Park Pond. In both lakes these samples came from regions of the lake with forested riparian zones. Riparian vegetation does not explain all of the variation in littoral leaf litter density however. The littoral sample with the lowest leaf litter density in Lancer Park Pond was collected along the same forested shoreline as the replicates with much greater littoral litter density and none of the samples collected from a forested shoreline in Woodland Court Pond had a littoral litter density as high as those found in Daulton Pond or Lancer Park Pond.

Overall leaf litter was a prominent pool of organic matter in all of the small man-made ponds in the study. Leaf litter alters lentic food webs (Kobayashi et al. 2011; Cottingham and Narayan 2013; Fey et al. 2015), nutrient cycles (McConnell 1968; France and Peters 1995), and energy flow (Hodkinson 1975). The presence and variability of leaf litter throughout the sediments of these small man-made ponds is likely to have profound effects on the ecology and biogeochemistry happening within the pond, and on the role of the pond in the watershed where it occurs.

The fine sediment organic matter content of the pond sediments was strikingly decoupled from the leaf litter density. Overall, the average percent sediment organic

matter in the ponds (10.3 ± 0.06 %) was very similar to the average $10.7 (\pm 0.05)$ % sediment organic matter measured in 16 agricultural impoundments in Iowa by (Downing et al. 2008) but less than the more organic rich (> 20 % organic matter) *gyttja* sediments typical of productive natural lakes in the temperate zone (Dean and Gorham 1998). The organic matter content of the sediment was not related to the density of leaf litter in the sediments nor did it differ significantly between the littoral and open water samples. These observations suggest that leaf litter inputs may not be an important driver of the variation in percent organic matter in the sediments. We cannot ascertain from our data the degree which leaf litter contributes to sediment organic matter because the lack of correlation may be due to the redistribution of fine sediment organic matter within the pond obscuring a spatial correlation. Interestingly the two ponds with permanent inlets (Lancer Park Pond and Woodland Court Pond) have the most homogeneous percent sediment organic matter, which may be a result of the higher energy in these systems. Wilck's Lake appears to have a bimodal distribution of sediment organic matter and this is likely due to the fact that this lake was created as a borrow pit, and the sediments may reflect the historical disturbance of the substrate. The greatest percent sediment organic matter and the greatest variation in sediment organic matter was found in Daulton Pond, which is mainly groundwater fed. This observation may be due to the lack of permanent surface water inputs which would limit the inorganic sediment load to the lake and maintain higher sediment heterogeneity.

The mean (\pm SD) leaf litter decomposition rate (k) measured for all 3 ponds in our study was $0.0030 (\pm 0.00005)$ which is lower than the average decay rate of 0.0059

d⁻¹ for woody plant litter in lakes in the review by Webster and Benfield (1986) and lower than what Webster and Benfield (1986) report for Magnoliaceae litter overall. Our mean decomposition rate was also lower than all but 5 of the 17 observations made in similar systems collected from the literature (Table 1). All of the studies with decomposition rates lower than those measured in our ponds came from boreal systems (Table 1, see Hodgkinson 1975a, and Oertli 1993) and of these, 3 were from recalcitrant species (Table 1, see Hodgkinson 1975a). Thus the decomposition rate of *L. tulipifera* litter in our study was among the lowest recorded rates for woody litter in the literature, and comparable to the litter decomposition rate high latitude systems.

Litter characteristics clearly affect the rate of leaf litter decomposition in aquatic systems (Webster and Benfield 1986; Gessner 2010), however it is unlikely that the slow rate of decomposition that we measured was due to the litter choice. Webster and Benfield (1986) report that Magnoliaceae litter has the second fastest breakdown rate of the woody plants in their review or breakdown rates, so *L. tulipifera* is not inherently resistant to decomposition.

The low rates of decomposition of the leaves in these ponds is likely partially related to the near absence of shredder activity. Potential shredding taxa (i.e., crayfish) were observed colonizing the leaf packs in Lancer Park Pond but there was no obvious evidence of shredding on the leaves recovered from any of the ponds (K. Fortino, personal observation). Shredders can dramatically accelerate leaf litter mass loss in streams (Cummins 1974; Webster and Benfield 1986; Wallace et al.

1999) and lakes (Bjelke 2005). The highly limited shredder fauna and the lack of shredder activity may have been due to low oxygen concentration within the leaf packs which could limit shredder colonization and feeding (Bjelke 2005). We did not measure the oxygen availability within the leaf packs but the leaves were mainly black in color when harvested, which is evidence of decomposition under anoxic conditions (Anderson and Sedell 1979). The soft sediments found in the ponds may have also limited shredder colonization and contributed to the slow decomposition rate of the leaves. Many of the leaf packs became partially buried in the pond sediments during the course of the incubation (K. Fortino, personal observation), which may have reduced the microbial decomposition of the leaf material (Danger et al. 2012).

We used coarse mesh litter bags for our litter incubation, which allowed for the colonization of macroinvertebrates into the leaf packs, however the lack of evidence of shredding activity and the low decomposition rates suggests that the litter mass loss was due mainly the microbial processes. A lack of shredder activity is a common observation in streams that have been affected by urbanization and thus leaf litter mass loss is mainly driven by a combination of microbial activity and physical abrasion (Paul et al. 2006). Despite the substantial accumulation of leaf litter resources in these ponds it is possible that, similar to urban streams, they do not provide suitable environmental conditions for shredders. In the ponds that we studied, physical abrasion would likely be near zero so we expect that virtually all of the leaf litter decomposition is due to microbial activity.

Our hypothesis that leaf litter decomposition would differ among ponds with different construction types and physical conditions was not supported by the data. All three ponds had similarly low decomposition rates despite their differences. The similarity in litter decomposition rate between the ponds suggests that pond construction and gross physical conditions are not substantially affecting microbial decomposition rate, which may respond more to local sediment variables that are more similar between the ponds. Another possibility is that interacting differences between the ponds offset their respective effects. For example, Campus Pond typically has the highest chlorophyll, suggesting abundant available nutrients (Table 2), which may have stimulated leaf litter decomposition (Gulis and Suberkropp 2003; Tant et al. 2013). However, Campus Pond also has the largest inlet which could increase sedimentation and offset the impacts of the nutrients.

Taken together our results indicate that leaf litter is being collected and retained by small man-made ponds. Further we found that within these ponds, leaf litter was decaying at among the slowest rates observed for aquatic systems. Given that these ponds are novel, man-made features of the watershed, we suggest that their presence leads to a substantial alteration of organic matter processing within the watershed, and serves as a sink for detrital organic matter.

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Figure Legends

Figure 1. Areal leaf litter density in small man-made ponds near Farmville VA. Each point represents a single Ekman sample from the lake. Points are randomly offset on the x-axis to make all points visible.

Figure 2. Percent organic matter of the soft sediment determined from loss on ignition at 550° C from the surveyed ponds (A) and in relation to the density of leaf litter in the sediments (B).

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Figure 1

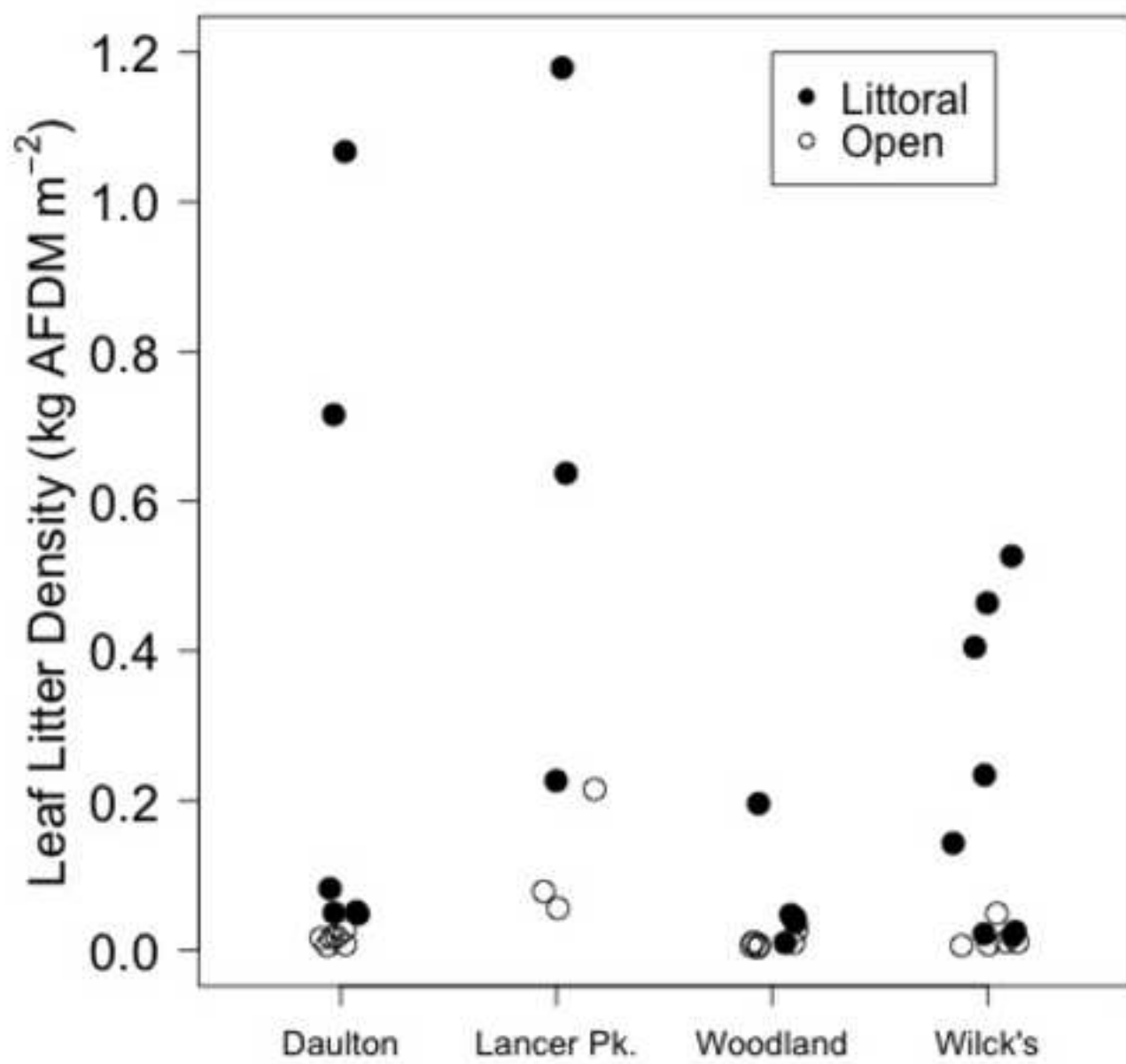


Figure 2

