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Leaf litter density and decomposition in small man-made ponds
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Abstract:	The input of terrestrial leaf litter into freshwater 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 on ecosystem function in lentic systems has received less attention. In particular the impact of leaf litter on trophic dynamics 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, 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 Liriodendron tulipifera leaves in coarse mesh leaf bags 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.

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Author Comments:	Dear Editor, Please consider our manuscript "Leaf litter density and decomposition in small man-made ponds" for publication in Aquatic Ecology. Our paper shows that small man-made ponds contain abundant terrestrial leaf litter and that this organic matter source decomposes slowly. Given that small ponds are a very abundant alteration to

watersheds in many parts of the world, our results indicate that small man-made ponds could represent an important alteration to organic matter cycling in watershed where they occur. Our findings are especially important because the impact of small ponds in general, and small man-made ponds especially on ecosystem processes have not received much study. Our study is only one of few estimates of the density of leaf litter within ponds and since leaf litter represents a key resource to many freshwater communities, having data on its abundance is important for understanding energy flow in pond ecosystems.

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

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

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9

10   **Abstract**

11   The input of terrestrial leaf litter into freshwater ecosystems supports aquatic food

12   webs and fuels microbial metabolism. Although the role of leaf litter subsidies to

13   streams has been studied extensively the effect of leaf litter on ecosystem function

14   in lentic systems has received less attention. In particular the impact of leaf litter on

15   trophic dynamics and biogeochemistry of small man-made ponds is virtually

16   unknown, despite the fact that these systems are extremely common and likely

17   represent a substantial modification to watersheds in the North America. We

18   measured the areal density of leaf litter and the rate of leaf litter decomposition in

19   small man–made ponds in central Virginia to determine the size of the leaf litter

20   pool in these systems, the rate at which leaf litter is decomposed, and the extent to

21   which pond characteristics alter leaf litter abundance or processing. We found that

22   the areal density of leaf litter in the ponds ranged between 3.4 and 1179.0 g AFDM

23   m^{-2}. The areal density of leaf litter was significantly greater in the littoral zones,

24   however leaf litter was present in the sediments throughout the pond. There was no

25   relationship between the areal density of leaf litter in the sediments and the percent

26   organic matter of the fine sediments, suggesting that leaf litter input is decoupled

27   from bulk sediment organic matter. The decomposition rate of *Liriodendron*

28   *tulipifera* leaves in coarse mesh leaf bags ranged between 0.0025 and 0.0035 d^{-1},

29   which is among the slowest litter decomposition rates recorded in the literature for

30   ponds and was unrelated to pond characteristics. Our results indicate that leaf litter

31   is an abundant and persistent pool of organic matter in the sediments of small man–

32   made ponds and it is likely to have a substantial effect on the trophic dynamics and

33   biogeochemistry of these systems.

34   **Introduction**

35   Ecosystem subsidies (i.e., the movement of resources across ecosystem boundaries

36   (Polis et al. 1997)) are an important part of organic matter cycling in freshwater

37   systems. The reciprocal transfer of resources between aquatic and terrestrial

38   systems is common (Nakano and Murakami 2001; Baxter et al. 2005), however the

39   input of terrestrial organic matter to aquatic systems is an especially significant flux

40   of material since, this subsidy has been shown to support metabolism and

41   secondary production in a majority of lentic and lotic ecosystems (Marcarelli et al.

42   2011). Organic matter subsidies from terrestrial to aquatic ecosystems are

43   dominated by detrital plant material either as dissolved (DOC) or particulate (POC)

44   organic carbon, and can substantially augment autochthonous organic matter

45   production (Hodkinson 1975a; Gasith and Hosier 1976; Wetzel 1984; Wetzel 1995;

46 Webster and Meyer 1997; Kobayashi et al. 2011; Mehring et al. 2014). Seasonal leaf

47 fall dominates the POC input into most temperate aquatic systems (Wallace et al.

48 1999) and this detrital material serves to stabilize variation in aquatic metabolism

49 (Wetzel 1984).

50 The effects of terrestrial leaf litter subsidies on freshwaters have received the most

51 attention in small lotic systems (Webster and Benfield 1986). In undisturbed lotic

52 systems, leaf mass loss begins with leaching, which is then followed by conditioning

53 of leaf material by microbial consumers, and finally consumption by shredding

54 macroinvertebrates (Cummins 1974; Gessner et al. 1999). Shredders can have a

55 particularly large impact on leaf breakdown rate and leaf litter may contribute

56 substantial material to stream secondary production (Wallace 1997; Graça 2001;

57 Eggert and Wallace 2003; Creed et al. 2009). Anthropogenic modifications to

58 watersheds associated with agricultural and urban land use do not consistently

59 change leaf litter processing rates in the stream channel (Bird and Kaushik 1992;

60 Huryn et al. 2002; Walsh et al. 2005; Hagen et al. 2006) but can have profound

61 impacts on the mechanisms of leaf breakdown (Bird and Kaushik 1992; Paul et al.

62 2006; Imberger et al. 2008) and thus alter the impact of detrital subsides.

63 Small impoundments (i.e., man-made ponds) are a common anthropogenic

64 alteration to watersheds globally (Downing et al. 2006; Downing 2010), but their

65 impact on leaf litter processing has received limited study. Impoundments have

66 been shown to alter litter processing rates downstream of dams (Short and Ward

67 1980; Mendoza-Lera et al. 2010; Tornwall and Creed 2016), but estimates of litter

68   processing within man-made ponds is limited (Table 1). Impoundment dramatically

69   alters the physical, chemical, and biological characteristics of the system. Not only

70   does the dam eliminate flow within the created pond or lake, but temperate ponds

71   typically stratify, producing heterogeneity in oxygen, and other dissolved

72   components (Wetzel 2001). Further, the reduction in flow produces a depositional

73   environment within the pond favoring the accumulation of soft sediments (Wetzel

74   2001). These changes to the chemical and physical environment of the pond result

75   in substantial differences in the composition of the pelagic and bethic communities

76   between the pond and the former lotic system (Ogbeibu 2002). Given that chemical,

77   physical, and biological (microbial and animal, consumers) conditions are central

78   leaf decomposition, it is likely that man-made ponds differ substantially from

79   surrounding lotic habitats with respect to leaf litter processing. The abundance of

80   the smallest ponds (< 0.1 km^2) is more than 2 orders of magnitude greater than

81   even modest sized lakes (1 km^2), and the number of small man-made ponds is

82   approaching the number of natural ponds (Downing 2010), indicating that small

83   man–made ponds represent an potentially important but understudied alteration to

84   aquatic organic matter cycling.

85   Our objectives for this study were to quantify the abundance of leaf litter and leaf

86   litter decomposition rate in small ponds in a moderately urbanized region of central

87   Virginia. We hypothesized that the ponds would contain abundant leaf litter and

88   that leaf mass loss would be slow relative to rates typical for lotic systems due to the

89   alteration of the physical, chemical, and biological conditions within the pond. We

90   further hypothesized that man–made ponds of different construction, even when

91   geographically close, would differ substantially in leaf processing rate, since leaf

92   litter decomposition is affected by temperature, nutrient availability, invertebrate

93   community composition, and temperature (Webster and Benfield 1986) and these

94   factors should be affected by the design and construction of man–made ponds.

95   **Methods**

96   **Study Site**

97   All of the ponds used in the study are located in central Virginia and are small man–

98   made ponds (Table 2). The ponds used for the quantification of leaf litter areal

99   density and sediment organic matter content were Lancer Park Pond, Daulton Pond,

100   Woodland Court Pond, and Wilck's Lake. Lancer Park Pond has an earth dam and a

101   permanent inlet and outlet. The pond is almost completely surrounded by second

102   growth forest. Daulton Pond is a headwater pond with an earth dam that does not

103   have a permanent inlet and is likely partially spring–fed. The riparian zone of

104   Daulton Pond is approximately 50% second growth forest and 50% mowed grass.

105   The littoral zone of Daulton Pond is mostly covered in an unidentified reed and

106   cattails (*Typha sp.*). Woodland Court Pond was created by an earth dam that is

107   drained by a stand–pipe. The pond has a permanent inlet and a riparan zone that is

108   about 30% second growth forest. The remaining portion of the riparian zone is

109   minimally landscaped disturbed land associated with an apartment complex.

110   Approximately 50% of the littoral zone of Woodland Court Pond is a patch of cattail

111   (*Typha sp.*). Wilck's Lake is the largest pond in the study and was created as a

112   borrow pit for the construction of a railroad. Wilck's Lake has no obvious inlet but is

113   drained by a stand-pipe into a permanent outlet. Wilck's Lake is part of a city park

114   and approximately 90% of the lake shoreline is second growth forest and the

115   remaining area is mowed grass.

116   The ponds used to determine litter decomposition rate were Lancer Park Pond,

117   Daulton Pond, and Campus Pond. Lancer Park Pond and Daulton Pond are described

118   above. Campus Pond is a stormwater retention pond with a permanent inlet that is

119   drained by a stand–pipe and is surrounded by landscaping that consists of small

120   trees and mowed grass. Campus Pond is enclosed by a vertical concrete wall, so it

121   has no natural littoral zone and is nearly uniform in depth.

122   **Leaf Litter Density and Sediment Organic Matter**

123   To estimate the areal density of leaf litter in the ponds we used an Ekman dredge to

124   collect sediment samples from the littoral and open water regions of each pond. We

125   collected 6 replicate littoral and 6 replicate open water samples from Daulton Pond,

126   Woodland Court Pond, and Wilck's Lake on 13 May 2013, 14 May 2013, and 14 June

127   2013 respectively. We collected 3 replicate littoral samples and 3 replicate open

128   water samples from Lancer Park Pond on 20 March 2013. Finally we collected 3

129   littoral and 6 open water samples from Wilck's Lake on 20 Febuary 2013. In all lakes

130   except Wilck's Lake, littoral samples were collected approximately 5 – 10 m from

131   the shoreline but the actual distance was not recorded. In Wilck's Lake, dense

132   overhanging vegetation along the shoreline prevented sampling and so littoral

133   samples were collected between 10 – 20 m from the shore. The open water samples

134   were collected away from the shoreline of the ponds.

135   The contents of the Ekman was homogenized in a plastic basin and a 10 ml sample

136   of the fine sediments was collected with a 30 ml plastic syringe with its tip cut off

137   (opening diameter = 1 cm). This sediment slurry was then placed in a pre–weighed

138   20 ml glass scintillation vial and dried at 50° C for at least 24 h. The remaining

139   material in the basin was sieved through a 250 μm mesh in the field and the

140   material retained by the sieve was preserved in 70% ethanol and transported back

141   to the lab. In the lab the preserved material was passed through a 1 mm sieve and

142   macroinvertebrates were removed. All remaining material retained by the sieve was

143   dried at 50 ^{o}C for 48 h and homogenized with a mortar and pestle. The dried fine

144   sediments and a subsample of the homogenized leaf litter were each ashed at 550 ^{o}C

145   for 4 h to determine the proportion of organic matter in the sample via loss on

146   ignition (LOI). To calculate the ash–free–dry–mass (AFDM) of the total leaf litter of

147   the sample the total dry mass was multiplied by the proportion of organic matter in

148   the sample. The areal density of leaf litter in the pond was then estimated by

149   normalizing the AFDM of the leaf litter to a square meter. We did not estimate the

150   areal mass of organic matter in the fine sediments because we did not have the total

151   dry mass of the sediments collected by the Ekman dredge.

152   **Leaf Litter Decomposition**

153   To determine the leaf litter decomposition rate in the ponds we measured the mass

154   loss rate of tulip poplar (*Liriodendron tulipifera*) leaf bags. Tulip poplar was chosen

155   for the litter species because it is common in the riparian zone of all of the ponds in

156   the study. The litter was collected by gently pulling senescent leaves from the tree.

157   Only leaves that released without resistance were used. The leaves were all

158   collected and air–dried during the fall of 2013. The leaf bags were assembled by

159   placing 5.0 g of intact leaves into plastic produce bags with approximately 9 mm^2

160   mesh. The bags were sealed with a zip–tie, attached to a small bag of rocks that

161   served as an anchor, and placed into the littoral zone of Campus Pond and Daulton

162   Pond on 22 October 2013 and into the littoral zone of Lancer Park Pond on 29

163   October 2013. To determine the mass lost due to handling and deployment, 5 bags

164   were immediately harvested following deployment at each site. Bags were

165   harvested by gently moving the bag into a 250 μm mesh net underwater and then

166   gently lifting from the pond. The bag and any material retained in the net were then

167   placed into an 11.4 L resealable plastic bag and returned to the lab. The contents of

168   the bag was gently rinsed over a 1 mm mesh sieve to remove macroinvertebrates

169   and then placed into a pre–weighed paper bag and dried at 50° C for at least 48 h.

170   The dried leaf material was then weighed and homogenized with a mortar and

171   pestle. This homogenized material was then ashed at 550° C to determine the AFDM

172   of the leaves. Following the initial sampling, 5 haphazardly chosen leaf bags were

173   sampled from each pond regularly using the same procedure. The number of days

174   that the remaining leaves were incubated in each pond is shown in Table 2.

175   **Statistical Analysis**

176   Differences in areal leaf litter density among ponds and between the littoral and

177   open water zones of all ponds was determined using ANOVA. The leaf litter density

178   was natural log transformed to homogenize the variance in the test of pond

179   differences and for the test between the littoral and open water samples. Specific

180   differences among ponds were assessed with a Tukey HSD post-hoc test. The

181   relationship between areal leaf litter density and the percent organic matter of the

182   sediments was assessed using linear regression.

183   The decay coeffecient (k) for the leaves in the litter bags in each pond were

184   determined by calculating the slope of the relationship between the natural log of

185   the percent leaf mass remaining by the number of days in the pond (Benfield 2007).

186   All statistical analysis was performed using R (R Core Team 2014).

187   **Results**

188   **Leaf Litter Density and Sediment Organic Matter**

189   The areal density of leaf litter in the ponds ranged between 0.00344 and 1.179 kg

190   AFDM m^{-2}. The greatest areal leaf litter densities were found in Daulton Pond and

191   Lancer Park Pond but in both cases the greatest areal densities were rather

192   exceptional values (Fig. 1). The total areal leaf litter density (i.e., littoral and open

193   water combined) differed significantly among the ponds ($F_{3,\ 38}$ = 3.955, p = 0.015).

194   The greatest areal leaf litter density was found in Lancer Park Pond with a mean ($\pm$

195   1 SD) density of 0.399 ($\pm$ 0.436) kg AFDM m^{-2}. However the areal leaf litter density

196   of Lancer Park Pond was only significantly different from Woodland Court pond,

197   which had a mean ($\pm$ 1 SD) areal density of 0.036 ($\pm$ 0.055) kg AFDM m^{-2}. The mean

198   ($\pm$ 1 SD) areal leaf litter density of Daulton Pond and Wilck's Lake were 0.175 ($\pm$

199   0.344) and 0.148 ($\pm$ 0.194) kg AFDM m^{-2}), respectively and were not significantly

200   different than each other or the other ponds.

201   In all the ponds, the greatest areal leaf litter densities were found in the littoral

202   portion of the pond (Fig 1). Across all the ponds areal leaf litter density of the littoral

203   portions of the ponds ranged between 0.0097 and 1.179 kg AFDM m^{-2} with a mean

204   ($\pm$ 1 SD) areal density of 0.283 ($\pm$ 0.347) kg AFDM m^{-2}, which is significantly greater

205   ($F_{1, 40}$ = 28, p < 0.0001) and much more variable than the areal leaf litter density of

206   the open areas of the ponds, which ranged between 0.0034 and 0.215, with a mean

207   ($\pm$ 1 SD) density of 0.030 ($\pm$ 0.0479) kg AFDM m^{-2} (Fig. 1).

208   The percent sediment organic matter of the ponds averaged ($\pm$ 1 SD) 10.3 ($\pm$

209   0.055)% across all ponds and ranged between a low of 0.73% in Wilck's lake and a

210   high of 22.3% in Daulton Pond. The mean ($\pm$ 1 SD) percent sediment organic matter

211   of Wilck's Lake was 6.17 ($\pm$ 3.65)%, which was significantly lower than any of the

212   other ponds ($F_{3, 37}$ = 6.664, p = 0.001). The percent sediment organic matter of the

213   sediments of Lancer Park Pond and Woodland Court pond were more

214   homogeneous, but not significantly different from the sediments of Daulton Pond

215   (Fig. 2). In all of the ponds, there was no significant difference between the open and

216   littoral sections of the pond ($F_{1, 39}$ = 0.963, p = 0.333), nor was there a relationship

217   between percent sediment organic matter and the density of leaf litter (r^2 = 0.0046,

218   p = 0.714)(Fig. 2).

219   **Litter Decomposition Rate**

220   Litter bags were deployed in Daulton Pond, Campus Pond, and Lancer Park Pond for

221   211, 209, and 204 days respectively. At the end of these incubations the mean ($\pm$ 1

222   SD) percent of the original 5 g of leaf mass remaining in Daulton Pond, Campus

223   Pond, and Lancer Park Pond was 45.3 % ($\pm$ 4.7 %), 42.3 % ($\pm$ 8.2 %), 43.2 % ($\pm$ 8.3

224   %), respectively. The three ponds had similar decay coefficients (k) but Daulton

225   Pond had the lowest rate at 0.0025 d^{-1}, followed by Campus pond and Lancer Park

226   Pond with rates of 0.0030 and 0.0035 d^{-1}, respectively. All of the litter bags had been

227   colonized by invertebrates but these were not collected quantitatively.

228   **Discussion**

229   Anthropogenic alterations to stream networks can alter leaf litter processing

230   relative to the undisturbed state. Commonly studied anthropogenic disturbances to

231   streams such as urbanization and agriculture have inconsistent impacts on leaf litter

232   processing (Bird and Kaushik 1992; Huryn et al. 2002; Walsh et al. 2005) but little is

233   known about the effect of man–made ponds on leaf litter processing, despite their

234   abundance. Our results show that small man-made ponds collect substantial

235   amounts of terrestrial leaf litter and have some of the slowest leaf litter

236   decomposition recorded in the literature. Thus, small man–made ponds represent

237   an important alteration to organic matter processing and specifically may serve as

238   an organic matter sink within watersheds where they occur.

239   The areal leaf litter densities measured in the man-made ponds in this study

240   support the observations of other authors that terrestrial detritus represents an

241   important subsidy to lentic systems (Hodkinson 1975b; Gasith and Hosier 1976;

242   Richey et al. 1978; Marcarelli et al. 2011). All of the ponds sampled had measurable

243   leaf litter in their sediments. We are not aware of any other studies that measure

244   leaf litter density in the sediments of man–made ponds in the same size class as we

245   studied, so it is not clear how representative our measurements are of the leaf litter

246   density of small man–made ponds globally. The only other lentic system for which

247   we were able to find a measure of leaf litter density was for an intermittent swamp

248   (Mehring et al. 2014). In this study the authors report that leaf litter densities range

249   between 1080 g m^{-2} following autumn leaf fall to 578 g m^{-2} in the summer (Mehring

250   et al. 2014), which is greater than all but the highest littoral values in the ponds we

251   sampled. Although we did not measure the flux of leaf material to the pond,

252   comparisons between the densities we observed and measures of leaf litter inputs

253   also serve to contextualize our observations. Gasith and Hosier (1976) report an

254   input of 1.64 g m^{-2} d^{-1} of leaf litter into the littoral zone of a Wisconsin lake. In a

255   forested mountain lake Rau (1976) recorded a much lower deposition rate of 0.173

256   g m^{-2} d^{-1} and France and Peters (1995) measured an even lower leaf litter flux of

257   approximately 0.04 and 0.02 g m^{-2} d^{-1} for the littoral zone of 4 lakes in Ontario. The

258   magnitude of these fluxes would not be able to supply the leaf litter densities that

259   we observed in the ponds in our study unless the litter was accumulating over many

260   years. Our litter decomposition rates indicate that 95% of leaf litter mass would be

261   mineralized in between 786 and 1065 days, which indicates that the litter does not

262   persist in these systems for sufficient time for such low deposition rates to be likely.

263   A more likely explanation is that the flux of leaf litter into the ponds in our study is

264   greater than what has been measured in high latitude lakes but not as high as those

265   recorded in the swamp by Mehring et al. (2014).

266   The greater density of leaf litter in the littoral samples also confirms the findings of

267   other authors that leaf litter accumulates predominantly near the shoreline (Gasith

268   and Hosier 1976; Rau 1976; France and Peters 1995). Unlike other studies of larger

269   systems (Rau 1976; France and Peters 1995) however, we found measurable leaf

270   litter in the center of the pond. Gasith and Hosier (1976) hypothesize that leaf litter

271   that enters the lake and floats for a period of time before being blown toward the

272   shore and sinking. The presence of measurable leaf litter in the offshore sediments

273   of the lakes in our study may be due to the small surface area of our ponds, which

274   would be insufficiently exposed to wind to exclude floating leaf litter from the open

275   water. This speculation is supported by the observation that the smallest lake in the

276   sample had the most leaf litter in the offshore samples, however the remaining lakes

277   all have a similar amount of offshore leaf litter despite size differences.

278   The degree to which sediment leaf litter derives from stream inputs in these ponds

279   is unknown but the significance of stream litter inputs is likely a function of stream

280   discharge, litter load, and pond volume. Lancer Park Pond, and Woodland Court

281   Ponds both have permanent first-order stream inlets, which likely serve as a

282   substantial source of litter, especially during high discharge events. Rau (1976)

283   found that litter inputs from intermittent streams around a mountain lake were

284   minor but the system in that study is not likely to be representative of the ponds in

285   our study. Although we know of no other estimation of stream leaf litter input to

286   ponds, the capacity of small streams to transport leaf litter is well known (Bilby and

287   Likens 1980). Despite the mechanisms involved, the presence of leaf litter in the

288   open water sediments of these small ponds indicates that any impact of leaf litter on

289   nutrient cycling and food–web processes extends beyond the littoral zone of small

290   ponds.

291   The degree of variability in leaf litter density within a pond was affected by the

292   location in the pond. The samples from littoral sediments were much more variable

293   than those from the open water sediments. The variability of the leaf litter density in

294   the littoral samples within each pond suggests that the factors affecting leaf litter

295   accumulation in the sediments are heterogeneous within a lake. Some of this

296   variation appears to be due to variation in riparian vegetation. France and Peters

297   (1995) found that riparian vegetation affected litter fall and that litter deposition

298   increased with the height, girth, and density of riparian trees. Rau (1976) reported

299   greater litter deposition along forested shorelines, relative to meadow and talus in a

300   mountain lake. In our study, the samples with the highest littoral leaf litter density

301   were from in Daulton Pond and Lancer Park Pond. In both lakes these samples came

302   from regions of the lake with forested riparian zones. Riparian vegetation does not

303   explain all of the variation in littoral leaf litter density however. The littoral sample

304   with the lowest leaf litter density in Lancer Park Pond was collected along the same

305   forested shoreline as the replicates with much greater littoral litter density and

306   none of the samples collected from a forested shoreline in Woodland Court Pond

307   had a littoral litter density as high as those found in Daulton Pond or Lancer Park

308   Pond.

309   Overall leaf litter was a prominent pool of organic matter in all of the small man–

310   made ponds in the study. Leaf litter alters lentic food webs (Kobayashi et al. 2011;

311   Cottingham and Narayan 2013; Fey et al. 2015), nutrient cycles (McConnell 1968;

312   France and Peters 1995), and energy flow (Hodkinson 1975b). The presence of and

313   variability of leaf litter throughout the sediments of these small man–made ponds is

314   likely to have profound effects on the ecology and biogeochemistry happening

315   within the pond, and on the role of the pond in the watershed where it occurs.

316   The fine sediment organic matter content of the pond sediments was strikingly

317   decoupled from the leaf litter density. Overall, the average percent sediment organic

318   matter in the ponds (10.3 ± 0.06 %) was very similar to the average 10.7 ($\pm$ 0.05)%

319   sediment organic matter measured in 16 agricultural impoundments in Iowa by

320   (Downing et al. 2008) but less than the more organic rich (> 20 % organic matter)

321   *gyttja* typical of productive natural lakes in the temperate zone (Dean and Gorham

322   1998). The organic matter content of the sediment was not related to the density of

323   leaf litter in the sediments nor did it differ significantly between the littoral and

324   open water samples. These observations suggest that leaf litter inputs may not be an

325   important driver of the variation in percent organic matter in the sediments. We

326   cannot ascertain from our data the degree which leaf litter contributes to total

327   sediment organic matter because the lack of correlation may be due to the

328   redistribution of fine sediment organic matter within the pond obscuring a spatial

329   correlation. Interestingly the two ponds with permanent inlets (Lancer Park Pond

330   and Woodland Court Pond) have the most homogeneous percent sediment organic

331   matter, which may be a result of the higher energy in these systems. Wilck's Lake

332   appears to have a bimodal distribution of sediment organic matter and this is likely

333   due to the fact that this lake was created as a borrow pit, thus the sediments may

334   reflect the historical disturbance of the substrate. The greatest percent sediment

335   organic matter and the greatest variation in sediment organic matter was found in

336   Daulton Pond, which is mainly groundwater fed. This observation may be due to the

337　lack of permanent surface water inputs which would limit the inorganic sediment

338　load to the lake and maintain higher sediment heterogeneity.

339　The mean ($\pm$ SD) leaf litter decomposition rate (k) measured for all 3 ponds in our

340　study was 0.0030 ($\pm$ 0.00005) which is lower that the average decay rate of 0.0059

341　d^{-1} for woody plant litter in lakes in the review by Webster and Benfield (1986) and

342　lower than what Webster and Benfield (1986) report for Magnoliaceae litter overall.

343　Our mean decomposition rate was also lower than all but 5 of the 17 observations

344　made in similar systems collected from the literature (Table 1). All of the studies

345　with decomposition rates lower than those measured in our ponds came from

346　boreal systems (Table 1, see Hodkinson 1975a, and Oertli 1993) and of these, 3

347　were from recalcitrant species (Table 1, see Hodkinson 1975a). Thus the

348　decomposition rate of *L. tulipifera* litter in our study was among the lowest recorded

349　rates for woody litter in the literature, and comparable to the litter decomposition

350　rate high latitude systems.

351　Litter characteristics clearly affect the rate of leaf litter decomposition in aquatic

352　systems (Webster and Benfield 1986; Gessner 2010), however it is unlikely that the

353　slow rate of decomposition that we measured was due to the litter choice. Webster

354　and Benfield (1986) report that Magnoliaceae litter has the second fastest

355　breakdown rate of the woody plants in their review of breakdown rates, so *L.*

356　*tulipifera* is not inherently resistant to decomposition.

357　The low rates of decomposition of the leaves in these ponds is likely partially related

358　to the near absence of shredder activity. Potential shredding taxa (i.e., crayfish)

359   were observed colonizing the leaf packs in Lancer Park Pond but there was no

360   obvious evidence of shredding on the leaves recovered from any of the ponds (K.

361   Fortino, personal observation). Shredders can dramatically accelerate leaf litter

362   mass loss in streams (Cummins 1974; Webster and Benfield 1986; Wallace et al.

363   1999) and lakes (Bjelke 2005). The highly limited shredder fauna and the lack of

364   shredder activity may have been due to low oxygen concentration within the leaf

365   packs which could limit shredder colonization and feeding (Bjelke 2005). We did not

366   measure the oxygen availability within the leaf packs but the leaves were mainly

367   black when harvested, which is evidence of decomposition under anoxic conditions

368   (Anderson and Sedell 1979). The soft sediments found in the ponds may have also

369   limited shredder colonization and contributed to the slow decomposition rate of the

370   leaves. Many of the leaf bags became partially buried in the pond sediments during

371   the course of the incubation (K. Fortino, personal observation), which may have

372   reduced the microbial decomposition of the leaf material (Danger et al. 2012).

373   We used coarse mesh litter bags for our litter incubation, which allowed for the

374   colonization of macroinvertebrates into the leaf bags, however the lack of evidence

375   of shredding activity and the low decomposition rates suggests that the litter mass

376   loss was due mainly the microbial processes. A lack of shredder activity is a common

377   observation in streams that have been affected by urbanization and in these systems

378   leaf litter mass loss is mainly driven by a combination of microbial activity and

379   physical abrasion (Paul et al. 2006). Despite the substantial accumulation of leaf

380   litter resources in these ponds it is possible that, similar to urban streams, they do

381   not provide suitable environmental conditions for shredders. In the ponds that we

382 studied, physical abrasion would likely be near zero so we expect that virtually all of

383 the leaf litter decomposition is due to microbial activity.

384 Our hypothesis that leaf litter decomposition would differ among ponds with

385 different construction types was not supported by the data. All three ponds had

386 similarly low decomposition rates despite their construction differences. The

387 similarity in litter decomposition rate between the ponds suggests that pond

388 construction and gross physical conditions are not substantially affecting microbial

389 decomposition rate, which may respond more to local sediment variables that are

390 more similar between the ponds. Another possibility is that interacting differences

391 between the ponds offset their respective effects. For example, Campus Pond

392 typically has the highest chlorophyll, suggesting abundant available nutrients (Table

393 2), which may have stimulated leaf litter decomposition (Gulis and Suberkropp

394 2003; Tant et al. 2013). However, Campus Pond also has the largest inlet which

395 could increase sedimentation and offset the impacts of the nutrients.

396 Taken together our results indicate that leaf litter is being collected and retained by

397 small man-made ponds. Further we found that within these ponds, leaf litter was

398 decaying at among the slowest rates observed for freshwater systems. Given that

399 these ponds are novel, man-made features of the watershed, we suggest that their

400 presence leads to a substantial alteration of organic matter processing within the

401 watershed, and may serve as a sink for detrital organic matter.

402 **Acknowledgements**

414   **Conflicts of Interest**

415   The authors declare that they have no conflict of interest.

416   **Tables**

417   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	*Ailanthus altissima*	0.5	0.008

Alonso et al. 2010	small man–made lake	central Spain	*Robinia pseudoacacia*	0.5	0.005
Alonso et al. 2010	small man–made lake	central Spain	*Fraxinus angustifolia*	0.5	0.009
Alonso et al. 2010	small man–made lake	central Spain	*Ulmus minor*	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	*Nymphaea ampla*	0.6	4.37
Gonçalves et al. 2004	brackish lagoon	Rio de Janeiro State, Brazil	*Typha domingensis*	0.6	0.17
Hodkinson 1975a	abandoned beaver pond	Alberta, Canada	*Salix*	0.35	0.0027

Hodkinson 1975a	abandoned beaver pond	Alberta, Canada	*Deschampsia*	0.35	0.0018
Hodkinson 1975a	abandoned beaver pond	Alberta, Canada	*Juncus*	0.35	0.0011
Hodkinson 1975a	abandoned beaver pond	Alberta, Canada	*Pinus*	0.35	0.0006
Oertli 1993	small man–made pond	Switzerland	*Quercus robur*	0.5 and 1.25 (data combined)	0.0014
Reed 1979	small natural lake	Ohio, USA	*Acer rubrum*	0.30	0.015 – 0.03
This study	small man-made ponds	Virginia, USA	*Liriodendron tulipifera*	0.4	0.0025 – 0.0035

418

419   Table 2. Descriptions of the ponds used in the study. The Secchi depth and

420   chlorophyll a concentrations are regularly measured in these ponds, so the values

421   given are representative of growing season conditions. Maximum Z is the maximum

422   depth ever recorded in the lake. Surface Area is calculated using the digitized outline

423   of the pond in from google maps with an online tool that calculates surface areas off

424   of google maps (https://www.daftlogic.com/projects-google-maps-area-calculator-

tool.htm). The latitude and longitude (Lat,Long) of the pond was measured at the approximate center of the pond using the "Whats here?" feature of google maps (https://www.google.com/maps/). Secchi Z is a representative Secchi depth recorded during the growing season. Chl a is a representative chlorophyll a concentration measured from the surface water during the growing season. Chlorophyll was measured with a Turner Designs Trilogy fluorometer using an acetone extraction following filtration of the pond water onto a GFF filter. Days Litter Bags Incubated is a list of the days the litter bags were in the water before being retrieved for those ponds used in the litter decomposition experiment. Chlorophyll a was not measured in Woodland Court Pond or Wilck's Lake.

Pond	Max Z (m)	Surface Area (ha)	Lat,Long (DD)	Secchi Z (m)	Chl a (μg L^{-1})	Days Incubated
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 Court Pond	2.0	0.30	37.284, -78.392	0.8	-	NA
Wilck's Lake	2.0	13.18	37.304, -78.415	0.6	-	NA

435

436 **Figure Legends**

437

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

441

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

445

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Figure 1

Figure 2