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1 **Water renewal along the aquatic continuum offsets cumulative**
2 **retention by lakes – implications for the character of organic**
3 **carbon in boreal lakes**

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1 7 **Abstract**
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4 8 The character of organic carbon (OC) in lake waters is strongly dependent on the
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6 9 time water has spent in the landscape as well as in the lake itself due to continuous
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8 10 biogeochemical OC transformation processes. A common view is that upstream lakes
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10 11 might prolong the water retention in the landscape, resulting in an altered OC character
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12 12 downstream. We calculated the number of lakes upstream for 24,742 Swedish lakes in
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14 13 seven river basins spanning from 56° to 68° N. For each of these lakes, we used a lake
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16 14 volume to discharge comparison on a landscape scale to account for upstream water
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18 15 retention by lakes ($T_{n \text{ tot}}$). We found a surprisingly weak relationship between the number
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20 16 of lakes upstream and $T_{n \text{ tot}}$. Accordingly, we found that the coloured fraction of organic
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22 17 carbon was not related to lake landscape position but significantly related to $T_{n \text{ tot}}$ when
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24 18 we analysed lake water chemical data from 1,559 lakes in the studied river basins ($R^2 =$
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26 19 0.21, $p < 0.0001$). Thus, we conclude that water renewal along the aquatic continuum by
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28 20 lateral water inputs offsets cumulative retention by lakes. Based on our findings, we
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30 21 suggest integrating $T_{n \text{ tot}}$ in studies that address lake landscape position in the boreal zone
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32 22 to better understand variations in the character of organic carbon across lake districts.
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41 24 **Keywords:** lake, landscape, time, organic carbon, colour
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1 26 **Introduction**

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4 27 The rate at which lake water is being renewed is crucial to time-dependent lake
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6 28 processes such as nutrient budgets (Vollenweider 1976; Hecky et al. 1993), carbon
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8 29 processing (Algesten et al. 2004; Battin et al. 2009) and lake water clarity (Schindler et
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10 30 al. 1996; Weyhenmeyer et al. 2012). During the last decade, more and more aquatic
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12 31 studies addressed a larger landscape, where it has been suggested that water may become
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14 32 older and the material in the water more processed the further down the water moves in
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16 33 the landscape (Egeberg et al. 1999; Steinberg 2003). This is certainly true for a single
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18 34 molecule travelling from headwaters via a series of lakes to the sea. However, lakes that
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20 35 are situated at low landscape positions not only receive water that has aged in lakes
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22 36 upstream but also from rainfall, groundwater and lateral tributary inflow. Thus, the age of
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24 37 water in lakes in the landscape is a result of complex runoff and mixing processes in the
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26 38 catchment (Lindström et al. 1997; Canham and Pace 2009).

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31 39 Studies addressing lake landscape position indicate that the presence of upstream
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33 40 lakes affects downstream water quality at both the temporal (Goodman et al. 2011) and
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35 41 the spatial (Larson et al. 2007) scale. In situations where water follows specific lake-
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37 42 chains from headwater lakes towards low landscape positions, material processing has
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39 43 been shown to occur (Soranno et al. 1999; Sadro et al. 2012). However, hydrological
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41 44 studies on drainage systems indicate that water residence time does not necessarily scale
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43 45 with catchment size, as observed for headwater systems (McGuire et al 2005; McDonnell
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45 46 et al. 2010) and along streams and rivers (Tokunaga 2003; Alexander et al. 2007).
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47 47 Alexander et al. (2007) demonstrated the important role of tributary streams for
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49 48 sustaining efficient water renewal throughout the entire drainage network of the
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51 49 northeastern United States. Martin and Soranno (2006) underpinned the relevance of such
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53 50 water renewal for lake-chains, as they identified stream connection as a major driver of
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55 51 variation in lake water chemistry and clarity across different landscape positions. The

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52 efficiency of water renewal occurring in a larger drainage network is therefore
53 fundamental to ecosystem functioning of lakes and reservoirs.

54 Lake volume and water discharge determine water retention by lakes, here referred
55 to as lake water retention time and used synonymously with water renewal time
56 (Schindler et al. 1992; Wetzel et al. 2001) and/or residence time (Monsen et al. 2002;
57 Algesten et al. 2004). A simple measure of water retention time for single lake water
58 bodies can be defined as the ratio between lake volume and mean discharge through the
59 lake outflow (T_n) and is frequently applied to indicate and compare general water
60 exchange properties of lakes (Bolin and Rodhe 1973; Monsen et al. 2002). In the
61 Experimental Lakes Area in Canada, comprising 58 small lakes with catchments of 0.1 to
62 8.4 km² in size, Schindler et al. (1992; 1996; 1997) have, for example, discussed OC
63 concentrations, nutrients and water colour based on T_n . Based on empirical models,
64 carbon sedimentation in lakes and reservoirs (Cole et al. 2007), carbon transport
65 (Weyhenmeyer et al. 2012) and mineralization (Algesten et al. 2004) have found to be
66 related to lake water retention times. Hence, the processing and transport of carbon in
67 lakes is a function of time. However, estimates of water retention times are frequently
68 applied and compared with limited knowledge of their actual distribution on a larger
69 landscape, and the cumulative water retention by lakes remains largely unknown.

70 This study addresses water retention by lakes and its relevance for the character of
71 OC. We used a dataset of 24,742 lakes (>0.01 km²) from seven river basins in Sweden,
72 covering a 12° latitudinal range. For each lake, we estimated two measures of water
73 retention time. The first estimated measure (T_n) corresponded to the mean water retention
74 time for a single lake (n), as defined above. The second estimated measure ($T_{n \text{ tot}}$)
75 included the sum of all lake volumes upstream of a lake (n), indicating a mean for the
76 water retention by lakes on a landscape scale (Algesten et al. 2004). We hypothesized that
77 lake landscape position is related to $T_{n \text{ tot}}$ and also to the coloured fraction of OC. We
78 further hypothesized that T_n is strongly related to the coloured fraction of OC as

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79 previously observed (Weyhenmeyer et al., 2012) but that the relationship becomes
80 stronger when T_n is replaced by $T_{n\text{ tot}}$. To test these hypotheses, we used lake
81 morphometric and hydrological data, as well as lake water chemical data from the
82 Swedish national lake monitoring program.

83

84 **Materials and Methods**

85 *Datasets*

86 Our lake dataset included 24,742 lakes larger than 0.01 km² from seven river
87 basins: (1) Lagan, (2) Mälaren, (3) Dalälven, (4) Ljungan, (5) Ångermanälven, (6)
88 Umeälven and (7) Kalixälven (Fig. 1). The lakes represent approximately 25.9 % of all
89 lake water bodies (>0.01 km²) in the Swedish Lake Registry (ca. 95,700 lakes) as
90 provided by the Swedish Meteorological and Hydrological Institute (SMHI). We chose
91 the seven river basins (Table 1) according to the following criteria: (1) estimates of long-
92 term (1961 to 1990) mean discharge were available for the entire basin, (2) volume
93 estimates for large lakes and reservoirs were available, (3) the river basins were
94 preferably large in size and (4) well distributed over Sweden. For each lake (n), we
95 estimated its volume (V_n), used the estimate of long-term mean discharge (Q_n), counted
96 the number of lakes (>0.01 km²) upstream, summed the lake volumes in the catchment
97 including the volume of the lake (n) at hand ($V_{n\text{ tot}}$) and determined our two measures of
98 water retention time (T_n , $T_{n\text{ tot}}$, see below).

99 Lake water chemistry data from the Swedish national lake monitoring program
100 were made available by the Swedish University of Agricultural Sciences (SLU). We used
101 water chemical data from lake water sampling campaigns run in the years 1995, 2000 and
102 2005 where a total of 1,559 lakes in the selected seven river basins were sampled. Some
103 lakes were sampled several times, while others were sampled only once. We analysed the

104 dataset for each year separately and additionally calculated a long-term lake-specific
105 median value. Sampled lakes were well distributed across the seven river basins (Fig. 1).
106 Sampling was conducted geographically from north to south by a helicopter. Samples
107 were taken at a depth of 0.5 m in the central part of each lake. Sampling periods stretched
108 from September until November, when lake waters underwent autumn water column
109 mixing and surface water samples become more representative of a lake's water
110 chemistry (Göransson et al. 2004). Variables considered in this study were absorbance at
111 420 nm, measured on filtered (0.45 μm) samples in a 5 cm quartz cuvette (AbsF₄₂₀;
112 reported with an analytical precision of 12 % according to method SS-EN ISO 7887 v.1)
113 and total organic carbon (TOC; reported with an analytical precision of 11 % according to
114 method SS-EN 1484 v.1). Absorbance data were converted to Napierian absorption
115 coefficients a_{420} [m^{-1}], Eq. 1:

$$a_{420} = \text{AbsF}_{420} \times \ln(10) \times L^{-1} \quad (1)$$

116 where AbsF₄₂₀ is the absorbance measured, ln(10) is the natural logarithm of 10
117 and L is the optical path-length [m], after Kirk (1994) and as recommended by Hu et al.
118 (2002). TOC in Swedish lakes generally contains 97 ± 5 % dissolved organic carbon
119 (DOC) (von Wachenfeldt and Tranvik 2008) and is therefore frequently used as a proxy
120 for DOC. We calculated the ratio a_{420} [m^{-1}] over TOC [mgL^{-1}] which reflects specific
121 absorbance at 420 nm and is thereby used as a measure of the character of OC (Wetzel
122 2001; Sulzberger and Durisch-Kaiser 2009).

124 *Lake volume estimates*

125 Information on measured lake volumes for a total of 1,263 lakes was available
126 from the Swedish Lake Registry (2009). Though these lakes represent only a minor
127 fraction of the lake dataset by count (5.1 %), they include the majority of large lakes. To

128 estimate the lake volume of the remaining 23,479 lakes, we applied an existing
129 empirically derived lake volume estimator after Sobek et al. (2011), Eq. 2 and Eq. 3:

$$\ln(V_{n \text{ unt}}) = 0.75 + 1.06 \times \ln(A) + 0.056 \times \gamma_{\max 50} \quad (2)$$

130 where $\ln(V_{n \text{ unt}})$ [-] is the natural logarithm of the lake volume estimate ($V_{n \text{ unt}}$)
131 [Mm^3] before correcting it for log-transformation bias, $\ln(A)$ the natural logarithm of the
132 lake area (A) [km^2] and $\gamma_{\max 50}$ the maximum slope [degree] within a 50 m buffer around
133 the lake water body (n). And

$$V_n = \exp(\ln(V_{n \text{ unt}})) \times \exp(0.5 \times s^2) \quad (3)$$

134 where V_n [Mm^3] is the lake volume estimate corrected for log-transformation bias
135 and s^2 the residual variance of the volume estimate. Eq. 2 explained 93 % of the
136 variability in lake volumes (V_n). The model was calibrated with known lake volumes
137 from the entire Swedish Lake Registry (6,943 lakes) and GIS derived morphological data
138 ($\gamma_{\max 50}$). The residual variance (s^2) used in Eq. 3 was 0.284 and was used to correct the
139 volume estimates for log-transformation bias; for more detailed information on this
140 model, we refer to Sobek et al. (2011). Published lake volumes were available for most
141 large lakes in the selected seven river basins, but there were 49 lakes (10.04 to 60.69 km^2)
142 beyond the size range ($>10 \text{ km}^2$) used by Sobek et al. (2011), for which published lake
143 volume estimates were not available. According to Sobek et al. (2011), extrapolation to
144 lakes $>10 \text{ km}^2$ was justified, and we therefore applied the volume estimator without
145 further calibration. Sobek et al. (2011) noted that their volume estimates performed well
146 as long as the lake count is kept high ($n \geq 15$). While the estimated volume of an
147 individual lake had a considerable degree of uncertainty, the relative error of cumulative
148 lake volumes was found to decrease during error propagation with the number of lakes by
149 $n^{(-0.5)}$, such that Eq. 2 is suitable to estimate lake volumes at a catchment or landscape
150 scale. In our analyses, volume estimates were rounded to 10^3 m^3 .

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152 *Long-term (30 years) mean discharge*

153 We used estimates of long-term mean discharge (Q_n) [m^3d^{-1}] at the outflow of
154 each lake (n), which were generated by the HBV (Hydrologiska Byråns
155 Vattenbalansavdelning) runoff model (Lindström et al. 1997) for the Swedish reference
156 period 1 January 1961 to 31 December 1990. Data were available from the SMHI as a
157 raster data file with a resolution of 50×50 m. The input data to the HBV runoff model are
158 observations of precipitation, air temperature and estimates of evapotranspiration. For
159 more detailed information on the HBV runoff model, we refer to Lindström et al. (1997).
160 We tested the accuracy of Q_n estimates by calculating long-term mean runoff [$mm\ yr^{-1}$]
161 for each lake, as the ratio between long-term mean discharge and catchment area, which
162 we compared to the published range of long-term mean runoff (140 to $1450\ mm\ yr^{-1}$) for
163 the respective time period. There were 213 lakes, all comparably small in size ($0.01 - 0.28$
164 km^2) which lay outside the published runoff range and were excluded, reducing an
165 original dataset of all available 26,264 lakes to a dataset of 26,051 lakes.

166

167 *Lake water retention time estimates*

168 We used Q_n and V_n to estimate conventional water retention times (T_n) for each
169 lake in our dataset, Eq. 4:

$$T_n = V_n \times Q_n^{-1} \quad (4)$$

170 where T_n [d], V_n [m^3] and Q_n [m^3d^{-1}] are the water retention time, lake volume and
171 long-term mean discharge estimates for a single lake (n). In addition, we estimated the
172 second measure of water retention time, which has earlier been used to indicate a mean
173 for the time water had been retained in lakes within the landscape (Algesten et al. 2004),
174 Eq. 5:

$$T_{n \text{ tot}} = V_{n \text{ tot}} \times Q_n^{-1} \quad (5)$$

175 where $T_{n \text{ tot}}$ [d] is the lake volume to discharge comparison between the summed
 176 lake volumes in the catchment of a lake (n), including the lake's own volume ($V_{n \text{ tot}}$) [m^3],
 177 and the estimate of long-term mean discharge (Q_n) [m^3d^{-1}] read at the outflow of the lake
 178 (n). $T_{n \text{ tot}}$ assumes that runoff from lakes upstream reaches lakes downstream.
 179 Evapotranspiration as well as groundwater are both considered in the water-balance of the
 180 HBV model used to estimate Q_n (Lindström et al. 1997). The SMHI notes that
 181 evapotranspiration is effective in the southern part of Sweden, where more than 50 % of
 182 the yearly precipitation may return back to the atmosphere. Replacement of runoff along
 183 flow and a weak connectivity amongst lakes may result in an overestimation of $T_{n \text{ tot}}$ for
 184 lakes low in the landscape. We therefore applied $T_{n \text{ tot}}$ (1) as a conservative measure of
 185 mean water retention by lakes on a landscape scale and (2) to observe how the ratio
 186 between cumulative lake volumes ($V_{n \text{ tot}}$) and long-term mean discharge (Q_n) changes
 187 from headwater lakes towards lakes at low landscape positions (Fig. 2). Quantifying T_n
 188 we identified water bodies ($>0.01 \text{ km}^2$) with theoretical water retention times of a few
 189 hours to days, implying that those water bodies rather resemble rivers than lakes.
 190 Excluding the lower 5 percentile, we limited our study to water bodies with a theoretical
 191 water retention time of 4 d and greater ($T_n \geq 4 \text{ d}$), leaving a final dataset of 24,742 lakes
 192 for analysis. However, we do test for the sensitivity of our results to this exclusion
 193 criterion (cut-off).

194 The ratio (R_v) between T_n and $T_{n \text{ tot}}$ is equivalent to the ratio between the lake's
 195 own volume (V_n) and the sum of the lake volumes upstream ($V_{n \text{ upstr}}$) including V_n , Eq. 6:

$$R_v = \frac{T_n}{T_{n \text{ tot}}} = \frac{V_n}{V_{n \text{ tot}}} = \frac{V_n}{V_{n \text{ upstr}} + V_n} \quad [\%] \quad (6)$$

196

197 *Statistical analysis*

198 We considered non-normality and heteroscedasticity (subgroups with unequal
199 variability) in our data by using the non-parametrical Wilcoxon method when testing for
200 differences between landscape positions. The strength of T_n and $T_{n\ tot}$ as predictors for
201 a_{420}/TOC was tested by running a multiple regression model on log-transformed data.
202 Statistical significance was assessed at $p < 0.05$. All statistical tests were carried out in
203 JMP, version 9.0.2. (SAS Institute, Inc., 2010).

205 **Results and Discussion**

206 *Lake water retention times in the landscape*

207 We found that conventional water retention times (T_n) for our dataset of 24,742
208 lakes ranged from 4 d to 10^4 d with the upper and lower 2.5 percentiles ranging from 7 to
209 1,207 d. The T_n distribution had a positive skew (median = 120 d, mean = 248 d). The
210 lower 2.5 percentile of the full T_n distribution was dominated by small lakes ($< 0.1\ km^2$)
211 situated within the main stems of the seven river basins. The upper 2.5 percentile
212 included headwater lakes where long-term mean water discharges were close to zero.
213 Such low Q_n for headwater lakes and the fact that Q_n strongly increased with an
214 increasing number of lakes upstream (Fig. 3b) explain why a non-parametric Wilcoxon
215 test showed significantly higher T_n values in the headwater group (median $T_n = 178$)
216 compared to the groups at low landscape positions ($p < 0.0001$; Fig. 3c). Removing the
217 cut-off for lakes with especially short water retention times ($T_n < 4$ d), the statistical
218 significance of our results remained unchanged. Our findings suggest that the majority of
219 lakes at low landscape positions experience increased water discharge, often resulting in a
220 more efficient exchange of water, when compared to headwater lakes.

221 Accounting for water retention by upstream lakes using $T_{n\ tot}$ for our 24,742 lakes
222 we found that $T_{n\ tot}$ ranged from 4 to 10^5 d with the upper and lower 2.5 percentiles
223 ranging from 15 to 1,288 d. Like for T_n , the $T_{n\ tot}$ distribution had a positive skew (median
224 = 178 d, mean = 326 d). In contrast to T_n however, $T_{n\ tot}$ showed lower values in the
225 headwater group compared to the groups at low landscape positions (non-parametric
226 Wilcoxon test: $p < 0.0001$; Fig. 3d). This pattern resulted from a strong increase in the
227 summed lake volumes (Fig. 3a; $V_{n\ tot}$) with an increasing number of lakes upstream that
228 exceeded the strong increase in discharge (Fig. 3b; Q_n) with an increasing number of
229 lakes upstream. Analysing each of the seven river basins separately, the significantly
230 increased $T_{n\ tot}$ values at low landscape positions remained similar in six of the seven river
231 basins (Lagan, Mälaren, Dalälven, Ljungan, Ångermanälven and Umeälven; Fig. 4).
232 Removing the cut-off for lakes with especially short water retention times ($T_n < 4$ d), the
233 statistical significance of our results remained unchanged.

234 We observed that more than 75 % of the lakes at high landscape positions showed
235 $T_{n\ tot}$ values < 365 d, implying that the water in these lake-networks is exchanged within
236 the course of one year (Fig. 4). In boreal Scandinavia, water retention times below one
237 year are primarily driven by strong seasonal runoff events, mainly the yearly spring
238 runoff after snowmelt but also strong rainfalls during summer (Lindström and Bergström
239 2004; Ågren et al. 2010). During runoff events, water retention times may drop to a
240 fraction of their theoretical long-term means, with strong environmental effects for
241 respective lake-ecosystems (Meili 1992; Ågren et al. 2010). Such seasonal variations are
242 not explicitly considered in our approach but are included in the long-term (1961-1990)
243 mean water discharge data. If processes in single lake ecosystems are studied, then high
244 frequency water discharge measurements are needed. Not until then underlying
245 mechanisms of water quality variations can be understood.

246 In headwater lakes (no lake > 0.01 km² upstream) $T_{n\ tot}$ corresponds to T_n by
247 definition. Headwater lakes made up 62 % of the lake count in our dataset. Thus, for the

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248 majority of lakes, conventional water retention time (T_n) is a suitable measure. Moving
249 away from headwater systems, however, differences between T_n and $T_{n\ tot}$ become
250 obvious. The strongest discrepancies between T_n and $T_{n\ tot}$, as expressed by the lowest R_v
251 values, are reached for lakes at low landscape positions. At these landscape positions, R_v
252 frequently showed values < 0.1 (Fig. 5a), implying that $T_{n\ tot}$ was more than 10 times
253 larger than T_n . At low landscape positions however, we also found some lakes that
254 showed comparatively high R_v values of ≥ 0.5 . High R_v values are reached when the
255 volume of a lake (n) is comparable to or larger than the summed lake volume upstream.
256 This is the case for the majority of the 114 largest lakes ($>10\ km^2$) which collectively
257 hold 74.5 % of the total lake volume in our dataset (Table 2). Such large lakes are located
258 at low landscape positions (circles, Fig. 5a). Consequently, the high $T_{n\ tot}$ values at low
259 landscape positions are strongly affected by large lakes. These results and median $T_{n\ tot}$
260 values $< 365\ d$ for lakes upstream (see above) suggest that lakes across all landscape
261 positions frequently receive water from lateral inputs, such as tributary or groundwater
262 inflow and/or from precipitation. Such efficient water renewal needs to be considered by
263 studies dealing with biochemical cycling on a landscape scale.

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264 A comparison between the total lake volume in the seven river basins and long-
265 term mean discharge has previously been assessed by Algesten et al. (2004) for Sweden's
266 21 river mouths. They found that water at the river mouths had been retained by lakes for
267 periods between 0.5 and 13.5 years. Our own estimates at seven river mouths (Table 1)
268 showed values between 0.4 and 3.5 years (156 to 1,265 d, respectively) and were 14.5 to
269 70.3 % lower than the values published earlier (ΔT ; Table 1). We interpret the deviating
270 results to differences in the assessment of lake volumes. We used newly published
271 information on lake volumes (see methods) that covered 89.2 % of the volume held by
272 the 114 large lakes mentioned above, as well as 73.3 % of the entire lake volume in our
273 dataset. Indeed, 26.7 % of the total lake volume had to be estimated, but by comparing
274 estimated lake volumes with published lake volumes (1,263 lakes), we received a slope

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275 close to 1 and a non-significant intercept ($p > 0.05$) indicating that our lake volume
276 estimates are reliable.

277 The $T_{n\ tot}$ approach is based on the following two fundamental assumptions that
278 need to be taken into consideration when $T_{n\ tot}$ is applied. (1) $T_{n\ tot}$ assumes that runoff
279 from lakes upstream reaches lakes downstream. Replacement of the respective runoff
280 along the aquatic continuum will result in an overestimation of $T_{n\ tot}$ for lakes at low
281 landscape positions, suggesting that water renewal may be even more efficient than
282 presented in this study. (2) $T_{n\ tot}$ assumes that a lake can be modelled as a well-mixed
283 system, which neglects periods of stratification. Thus, $T_{n\ tot}$ indicates a long-term mean
284 for water retention by lakes on a landscape scale and should not be confounded with more
285 elaborate measurements of residence time (Bolin and Rodhe 1973) and age (Zimmerman
286 1988), which assess the fate of solutes and particles travelling through a lake system
287 (Monsen et al. 2002).

288

289 *Lake water retention times and the character of organic carbon*

290 In accordance with previous results (Meili 1992; Schindler et al. 1992), we found
291 that T_n relates to the coloured fraction of OC in lakes, here defined as a_{420}/TOC . A
292 relationship between T_n and a_{420}/TOC was significantly negative but had a low coefficient
293 of determination (Fig. 6a; $R^2 = 0.11$, $p < 0.0001$). It has been argued that a preferential
294 colour loss along a T_n gradient is primarily the result of solar radiation induced OC
295 mineralization (Morris and Hargreaves 1997; Vähätalo and Wetzel 2004). Additionally,
296 in-lake processes such as microbial degradation and flocculation with consequent
297 sedimentation are known to result in a loss of the coloured fraction of OC (Tranvik 1998;
298 von Wachenfeldt et al. 2008; Köhler et al. 2012). OC can also be produced in the lake,
299 which usually is more transparent and labile than its terrestrial counterpart (Findlay and
300 Sinsabaugh 2003; Steinberg 2003). Consequently, the presence of upstream lakes has an

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301 effect on the OC character that is found downstream, both in terms of the amount and in
302 the light-absorbing properties (Larson et al. 2007 and Sadro et al. 2012).

303 Since the conventional retention time estimator T_n does not account for any water
304 retention and carbon processing by upstream lakes, we expected an improvement in the
305 relationship between lake water retention and a_{420}/TOC when we replaced T_n by $T_{n \text{ tot}}$.
306 Such an improvement was achieved for non-headwater lakes (911 lakes with $T_n \neq T_{n \text{ tot}}$).
307 First of all we were able to raise the coefficient of determination from 0.11 to 0.21 (Fig.
308 6b), and secondly we found that $T_{n \text{ tot}}$ was the stronger predictor for a_{420}/TOC when we
309 ran a multiple regression model with both log-transformed T_n and $T_{n \text{ tot}}$ as explanatory
310 variables ($t = -9.77$, $p < 0.0001$ and $t = -1.97$, $p = 0.0497$, respectively). The coefficient of
311 determination became exceptionally high when we grouped our data and related median
312 water retention times to median a_{420}/TOC values (Fig. 6a and 6b). An improved relation
313 to the coloured fraction of OC by using $T_{n \text{ tot}}$ instead of T_n supports the concept that the
314 character of OC in boreal lakes is related to the time OC has spent in lakes within the
315 landscape.

316 Replacing $T_{n \text{ tot}}$ by lake landscape position, we found a significant ($p < 0.05$)
317 decrease in a_{420} (Fig. 7a) and TOC (Fig. 7b) but not in a_{420}/TOC (Fig. 7c). These results
318 suggest that there is either no preferential loss of the coloured fraction of OC across
319 landscape positions or that highly coloured OC is supplied from lateral inflows at the
320 same rate as it is lost by mineralization and sedimentation. Previous studies addressing
321 lake landscape position suggested that changes in OC quantity and quality depend on
322 hydrologic connectivity (Martin and Soranno et al. 2006) and lake-network structure
323 (Soranno et al. 1999). Thus, measures of the character of OC, such as a_{420}/TOC , may
324 increase or decrease when following a specific lake-chain. Moving from specific lake-
325 chains to a large scale across lake districts, as done in our study, increases variability and
326 may obscure patterns that have been reported from within specific lake-chains (Sadro et
327 al. 2012). Consequently studies that address changes within specific lake-chains, e.g. the

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328 studies by Kratz et al. (1997) and Kling et al. (2000), differ from studies like ours that test
329 differences across lake landscape positions based on data from numerous lake districts.

330 Seeing lakes from a large landscape perspective and assessing lakes beyond
331 specific lake-districts become especially relevant in the carbon rich boreal zone, where
332 river basins may hold several thousand lakes and the bulk lake area and volume is
333 unevenly distributed (Table 2). As an integral part of the boreal landscape, lakes delay
334 surface water runoff, giving time for carbon processing to occur, and thereby acting as
335 regulators of carbon cycling (Cole et al. 2007; Tranvik et al. 2009). Seeing lakes from a
336 landscape perspective may become increasingly relevant in the future, as lakes are
337 monitored, modified and managed for such endeavours as hydropower generation (Barros
338 et al. 2011) and multi-lake ecosystem management (Soranno et al. 2010).

339

340 **Conclusions**

341 We conclude from our results that lake landscape position does not reflect well
342 how long the water has travelled in a boreal landscape, limiting its use in explaining
343 water retention time dependent processes. While T_n is a useful tool to indicate lake water
344 retention for single lake water bodies, we recommend using $T_{n\ tot}$ for large-scale
345 approaches. Since we found a strong relationship between $T_{n\ tot}$ and the character of OC in
346 the landscape for 1,559 lakes, we suggest that $T_{n\ tot}$ might also be a useful measure to
347 explain variations of other nutrients in the landscape.

348

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Table 1 Dataset by river basins; area of river basin (size), highest point (z_{\max}), number of lakes larger than 0.01 km^2 (lake count), summed lake volumes ($V_{n \text{ tot}}$), long-term (1961 to 1990) mean flow as discharge at the river mouth (Q_{sea}), and the ratio between $V_{n \text{ tot}}$ and Q_{sea} (T_{sea}). The percentage ΔT presents the difference between T_{sea} and earlier estimates published by Algesten et al. (2004)

ID	river basin	size [km ²]	z_{\max} [m a.s.l.]	lake count [-]	$V_{n \text{ tot}}$ [Mm ³]	Q_{sea} [m ³ s ⁻¹]	T_{sea} [d]	ΔT [%]
1	Lagan	6,452	372	737	2,641	83	368	-
2	Mälaren	22,650	490	2,138	22,069	202	1,265	-
3	Dalälven	28,621	1,436	5,241	17,161	357	557	-51 %
4	Ljungan	12,851	1,577	2,187	5,340	150	412	-70 %
5	Ångermanälv.	31,079	1,564	5,450	29,502	520	657	-25 %
6	Umeälven	26,815	1,751	5,710	17,162	430	462	-37 %
7	Kalixälven	18,130	2,092	3,279	3,060	227	156	-15 %

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Table 2 Lake count and volumes per lake size class A to E

SMHI size classes [km ²]	lake count [-, %]		lake area [km ² , %]		lake volume [Mm ³ , %]		
E	0.01 – 0.1	18128	73.2 %	5,242	50.5 %	1,606	1.6 %
D	0.1 – 1	5410	21.9 %	2,943	28.3 %	5,983	6.2 %
C	1 – 10	1090	4.4 %	1,630	15.7 %	17,121	17.7 %
A – B	> 10	114	0.5 %	567	5.5 %	72,225	74.5 %
Total		24,742	100.0 %	10,382	100.0%	96,935	100.0 %

Fig. 1 Geographic location of the seven river basins in our dataset; Lagan (1), Mälaren (2), Dalälven (3), Ljungan (4), Ångermanälven (5), Umeälven (6), Kalixälven (7). Lakes sampled by the Swedish national lake monitoring program in 1995, 2000, 2005 marked (black dots)

Fig. 2 (a) An exemplary lake (n) with three lakes upstream. The lake volume to flow comparison $T_{n \text{ tot}}$ is indifferent of the flow and lake distribution upstream of the lake (n) at hand. The summed lake volume ($V_{n \text{ tot}}$) includes the lake (n) at hand. (b) Following a lake series downstream, $T_{n \text{ tot}}$ will decrease where flow as discharge (Q_n) accumulates faster than the summed lake volume ($V_{n \text{ tot}}$) and conversely increase where $V_{n \text{ tot}}$ accumulates faster than Q_n

Fig. 3 Distribution (median, 50 % and 90 % quantile ranges) of (a) summed lake volumes $V_{n \text{ tot}}$ in the catchment of each lake, (b) long term (1961 – 1990) mean discharge (Q_n) at the outflow of each lake, (c) water retention time T_n for each lake. Asterisks indicate significance levels (* $p < 0.05$, ** $p < 0.001$, *** $p < 0.0001$) for a decrease in the median T_n when compared to the headwater group (hg). Crosses mark medians for lakes sampled. (d) Water retention time $T_{n \text{ tot}}$ where the increase in median $T_{n \text{ tot}}$ from the headwater group towards the most downstream group is marked (dark-grey). Asterisks indicate significance levels (* $p < 0.05$, ** $p < 0.001$, *** $p < 0.0001$) for an increase in the median $T_{n \text{ tot}}$ when compared to the headwater group (hg). Crosses mark medians for lakes sampled. For all figure parts lakes grouped by no, one, 2 – 5, 6 – 10, 11 – 100 and >100 lakes (>0.01 km²) upstream

Fig. 4 Distribution (median, 50 % and 90 % quantile ranges) of $T_{n \text{ tot}}$ in days for each river basin, with $T_{n \text{ tot}} = 365$ d marked (dashed-line). Lakes grouped by no, one, 2 – 5, 6 – 10, 11 – 100 and >100 lakes (>0.01 km²) upstream. Asterisks indicate significance levels (* $p < 0.05$, ** $p < 0.001$, *** $p < 0.0001$) for an increase in the median $T_{n \text{ tot}}$ when compared to the headwater group (hg). For all figure parts lakes grouped by no, one, 2 – 5, 6 – 10, 11 – 100 and >100 lakes (>0.01 km²) upstream

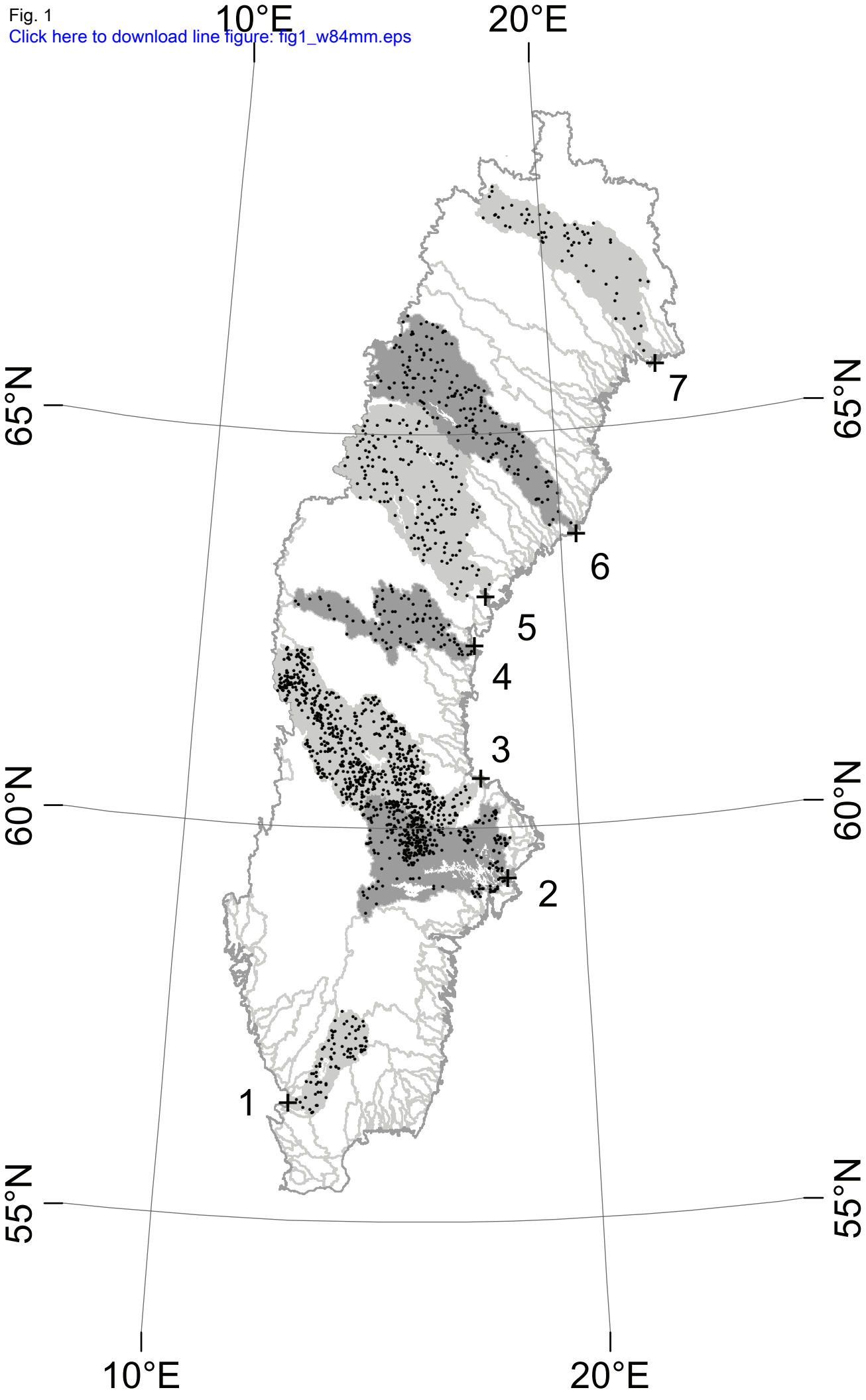
Fig. 5 (a) Distribution (median, 50 % and 90 % quantile ranges) for T_n versus $T_{n \text{ tot}}$ as ratio R_v . Lakes grouped by no, one, 2 – 5, 6 – 10, 11 – 100 and >100 lakes (>0.01 km²) upstream

(b) Direct comparison between T_n and $T_{n\ tot}$ for the entire dataset. For both figure parts $R_v = 1.0$, 0.5 and 0.1 marked (dashed-line), and the 114 largest lakes ($>10\ km^2$) marked (circles)

Fig. 6 Relationship between (a) T_n and a_{420}/TOC , (b) $T_{n\ tot}$ and a_{420}/TOC , respectively for 911 non-headwater lakes (grey dots) with the regression statistics (data) and the regression curve (curved line). Shown are also median values for grouped data (black circles) with standard deviations (black bars) and the regression statistics (median)

Fig. 7 Distribution (median, 50 % and 90 % quantile ranges) of a_{420} , TOC and a_{420}/TOC for 1,559 lakes sampled. Asterisks indicate significance levels (* $p < 0.05$, ** $p < 0.001$, *** $p < 0.0001$) for a decrease in a_{420} , TOC and a_{420}/TOC when compared to the headwater group (hg). Changes in a_{420}/TOC across groups of different landscape positions were non-significant ($p > 0.05$). Lakes grouped by no, one, 2 – 5, 6 – 10, 11 – 100 and >100 lakes ($>0.01\ km^2$) upstream

Fig. 1
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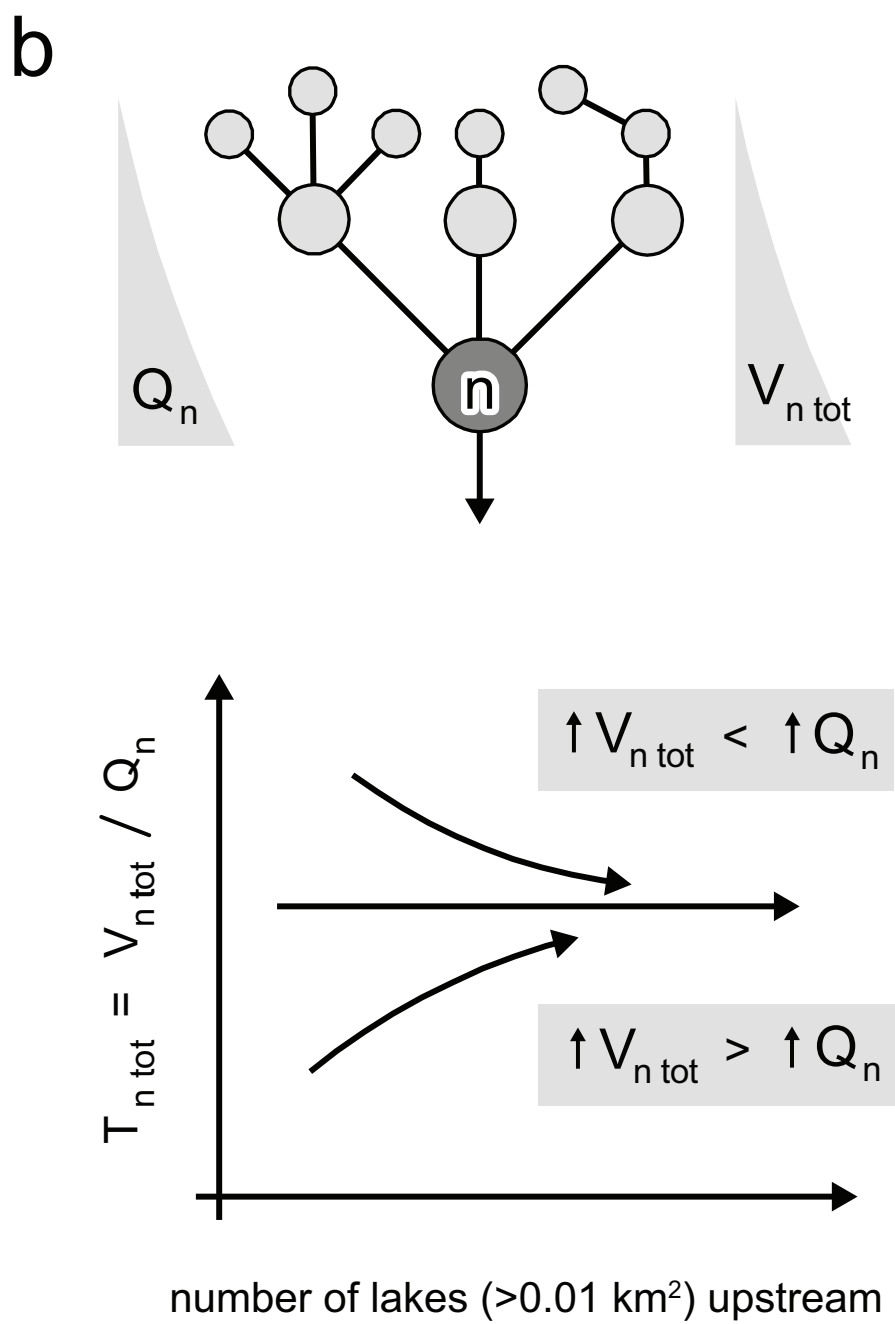
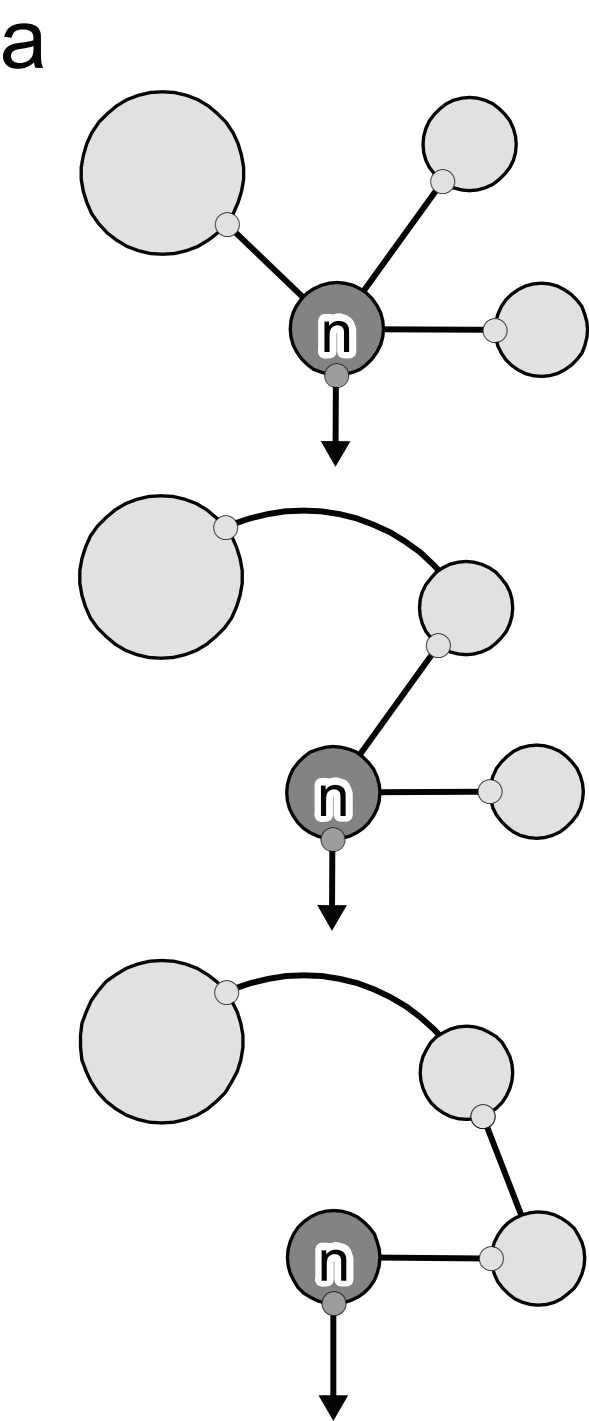


Fig. 3
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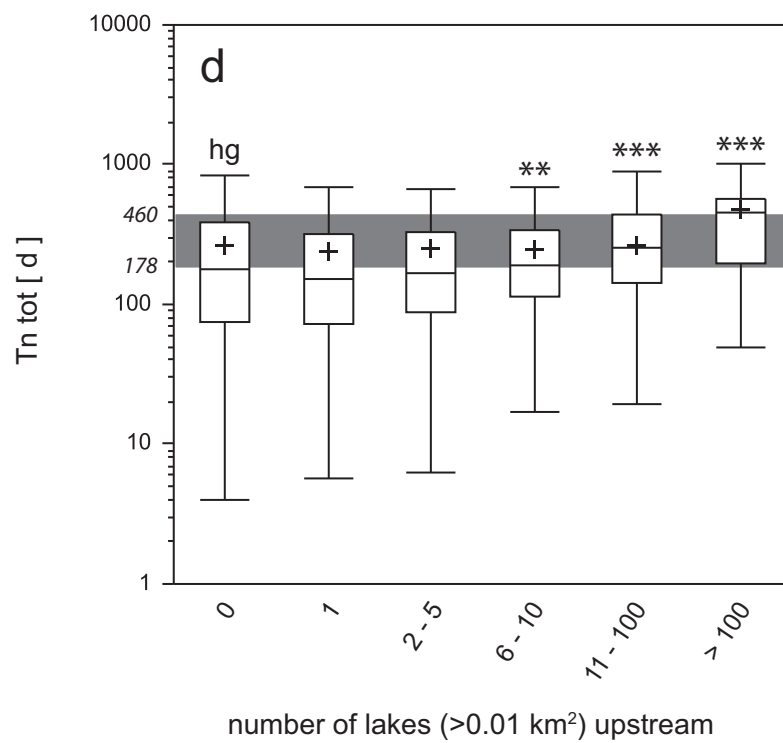
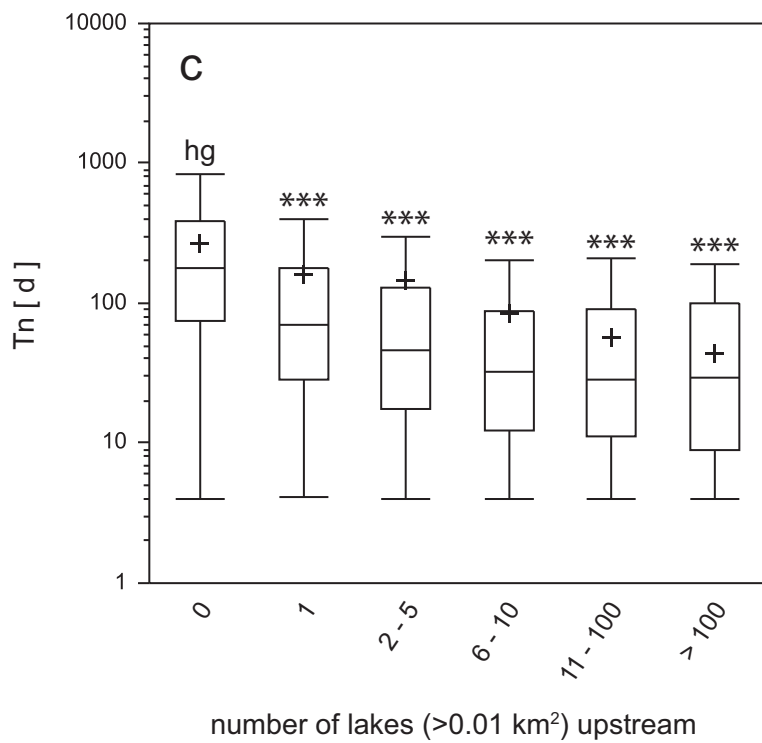
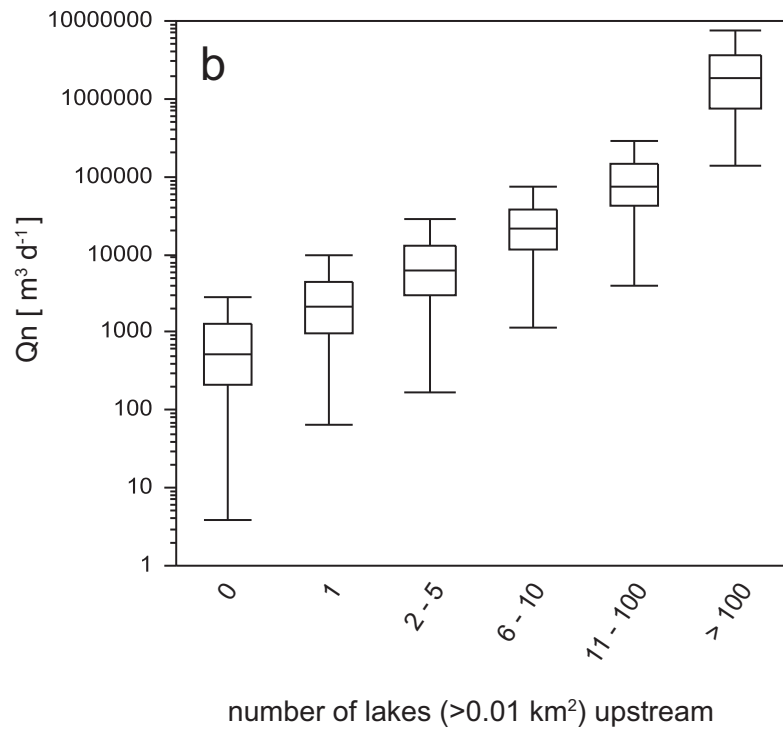
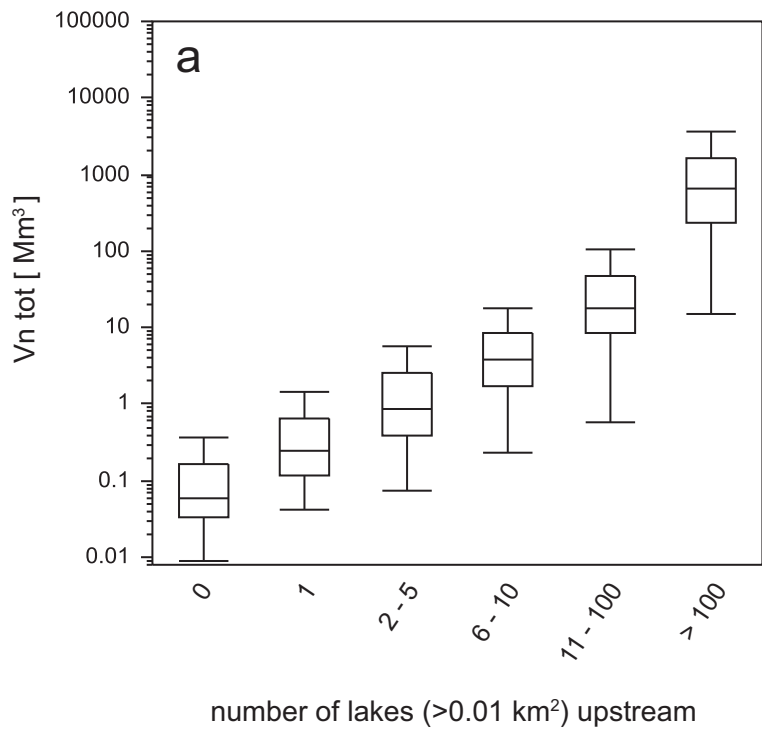


Fig. 4

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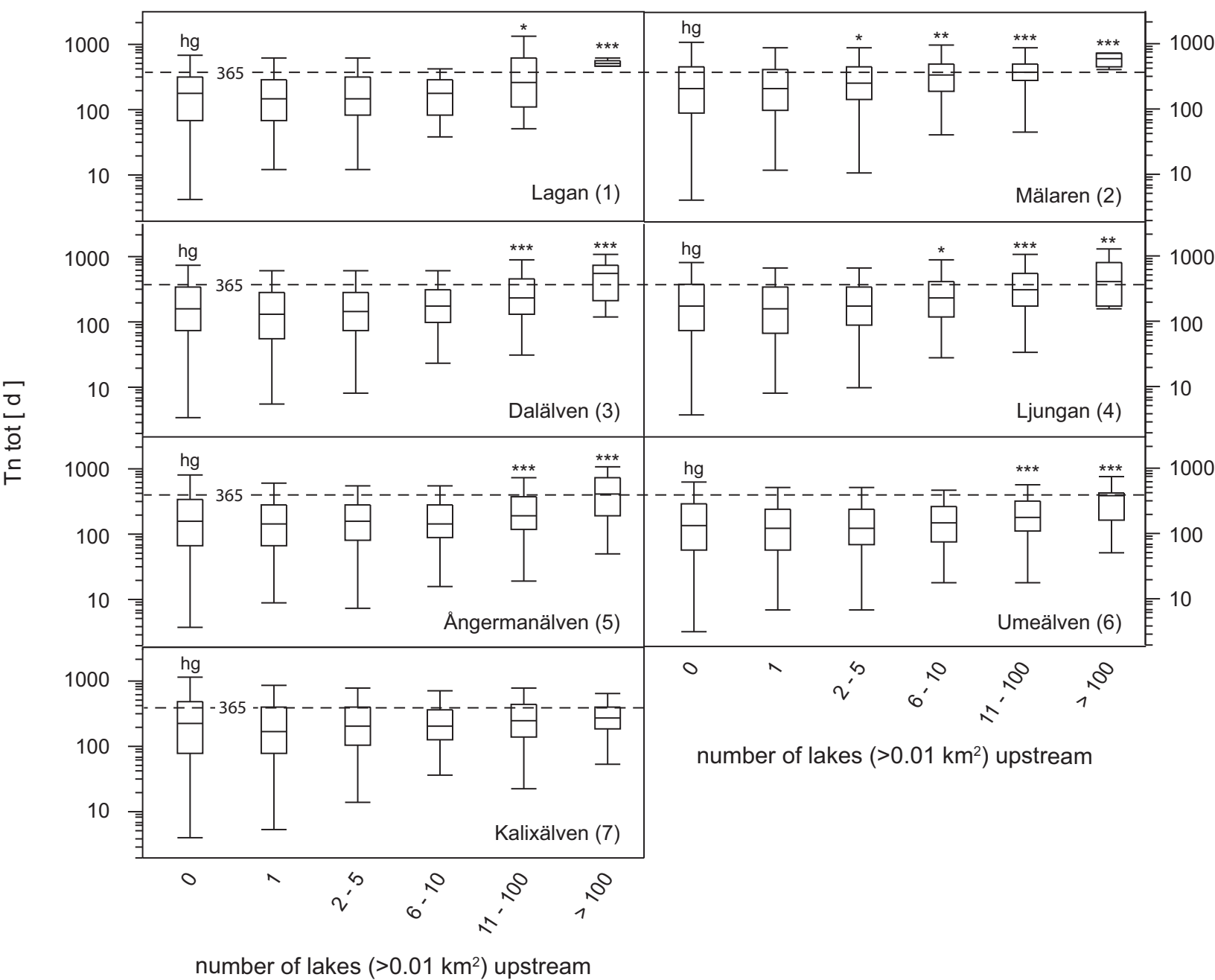


Fig. 5
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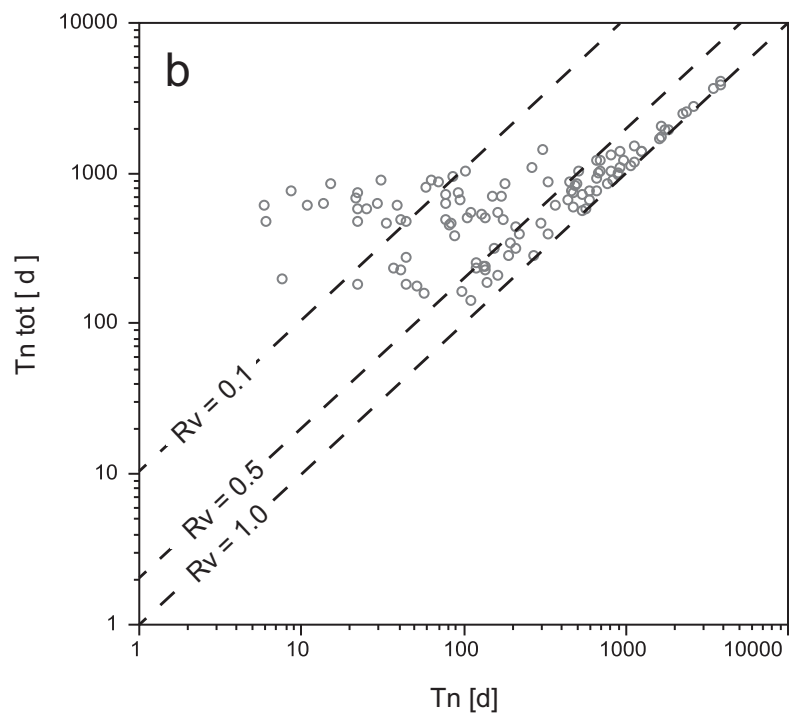
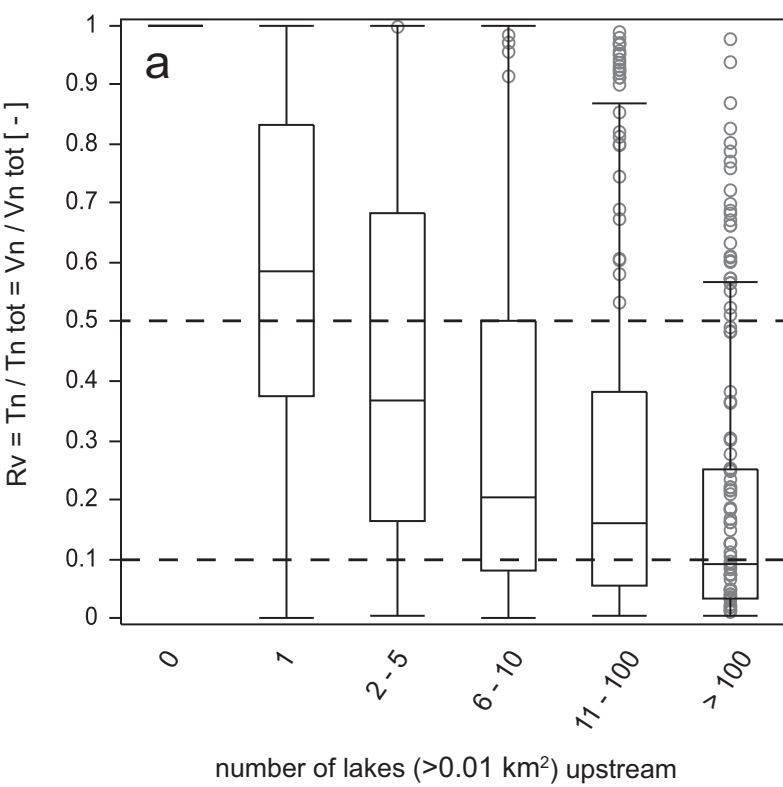
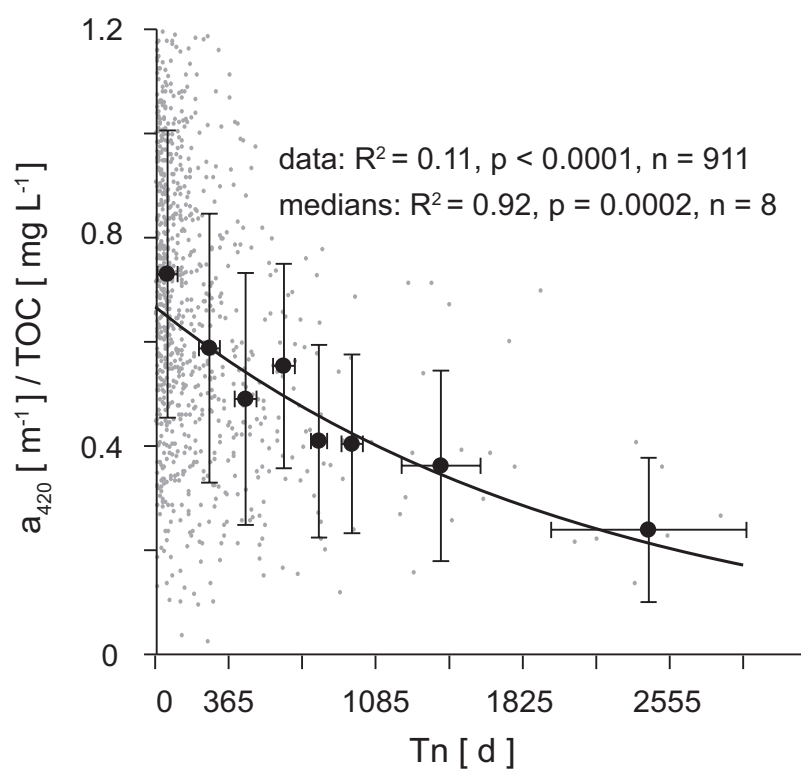


Fig. 6

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a



b

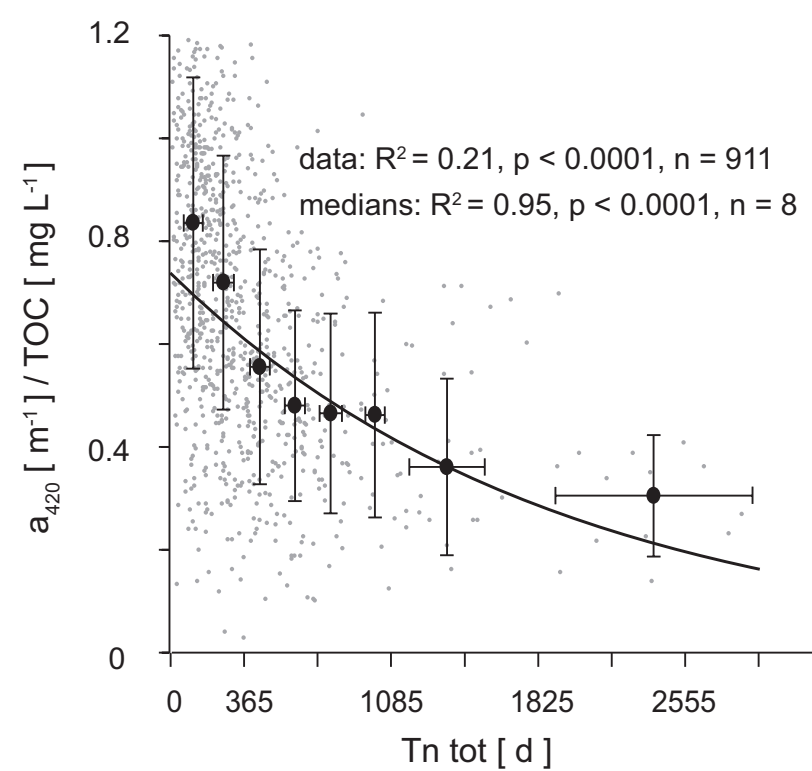


Fig. 7

[Click here to download line figure: fig7_w84mm.eps](#)