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Long-term C accumulation and total C stocks in boreal lakes in northern Québec

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[1] Here we assess total sediment organic C stocks and long-term C accumulation rates in 13 boreal lakes in northern Québec spanning a wide range of morphometric shapes. The lake basins were mapped using a sub-bottom profiler to obtain total sediment volume, which we combined with organic carbon profiles from Holocene cores to obtain total C mass. The estimated long-term areal C accumulation rates averaged 3.8 g C m^{-2} yr^{-1}, lower than previous reports for other boreal and temperate regions. The difference relative to previous studies may have resulted from our use of the detailed echosounding mapping approach, which yields more realistic estimates of total sediment volume. Total sediment C stocks were not related to lake trophic status or to DOC concentration, but rather to lake area and to the lake dynamic ratio (√lake area/mean water depth). We hypothesize that scaling of C accumulation to lake morphometry is more a reflection of the intrinsic capacity of lakes to retain carbon. We show that C loading does in fact play a significant role in the patterns of C accumulation in lakes, but that this role is strongly modulated by both lake size and shape, which in turn determine the ability of lakes to retain the carbon that has been loaded. Upscaling to the regional level using the empirical lake size relationships developed here results in an areal-weighted average C stock of 23 kg C m^{-2} (per unit of lake area), or 3.8 kg m^{-2} (per unit landscape), which represents around 25% of the total landscape C storage in this boreal region. Because of the lake-size scaling of C accumulation, the total lake C stocks at the regional level depend not only on the total lake area, but more importantly on the local lake size distribution.

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1. Introduction

[2] There is converging evidence suggesting that the contribution of inland waters to the global carbon budget has been grossly underestimated [*Dean and Gorham*, 1998; *Cole et al.*, 2007; *Prairie*, 2008; *Battin et al.*, 2009]. Lakes are generally net sources of CO_2 and CH_4 to the atmosphere [*Kling et al.*, 1992; *Cole et al.*, 1994; *del Giorgio and Peters*, 1994; *Sobek et al.*, 2003; *Bastviken et al.*, 2011] and these emissions have been shown to be significant at local, regional and global scales [*Algesten et al.*, 2005; *Tranvik et al.*, 2009]. Somewhat counter-intuitively, lakes also constitute an important permanent sink of carbon within their landscape, because they accumulate both inorganic and organic C in their sediments [*Dean and Gorham*, 1998; *Campbell et al.*, 2000; *Kortelainen et al.*, 2004; *Cole et al.*, 2007; *Tranvik et al.*, 2009]. Earlier studies had estimated the global lake C sink at around 0.04 Pg C y^{-1} [*Dean and Gorham*, 1998] but recent syntheses have suggested much higher rates of between 0.2 and 0.6 Pg C y^{-1} for inland waters [*Cole et al.*, 2007; *Battin et al.*, 2009]. These revised values are in the same order of magnitude as the global oceanic C sink [*Cole et al.*, 2007]. In this regard, *Molot and Dillon* [1996] had estimated that approximately 120 Pg C are globally stored in boreal lake sediments over the Holocene, whereas extrapolation of the study by *Kortelainen et al.* [2004] from Finland yields a considerably lower global estimate, in the order of 19–27 Pg C. A recent study has concluded that total C accumulation in European lakes is in the order of 1.25 Mt C yr^{-1}, somewhat lower than previously thought, and has further highlighted major weaknesses in current estimates of both regional lake distributions, sediment volume and C contents [*Kastowski et al.*, 2011]. Although there is clearly a large degree of uncertainty in the current estimates of regional or global lake C storage, all converge on the important role of lakes as C sinks.

[3] A substantial portion of the global lake C storage is expected to occur in boreal landscapes [*Molot and Dillon*,

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1996; *Kortelainen et al.*, 2004], and although lakes cover between 5 to over 30% of the total surface area in these regions, there have been only a limited number of studies that have addressed the contribution of lakes to regional C storage in northern latitudes. Based on measurements carried out in northern Ontario (Canada), *Molot and Dillon* [1996] calculated that on average, 24 Tg of C is annually stored in the sediments of boreal lakes. This represents roughly twice the amount of C stored in plant biomass in the boreal biome, and around a quarter of the total C that is regionally stored in boreal peatlands [*Molot and Dillon*, 1996]. Similarly, *Kortelainen et al.* [2004] concluded that C storage in Finnish lakes was about threefold greater than that in soils, and about a third of that in peatlands in the boreal Finnish landscape expressed per unit area, whereas *Anderson et al.* [2009] showed that C stored in lakes represented about half of total soil C in Greenland. On the other hand, *Campbell et al.* [2000] concluded that lake C storage represented about 15% of the C stored in peatlands in northern Alberta (Canada). These scattered regional estimates converge to suggest that boreal and sub-arctic lakes play a role in regional C accumulation and long-term storage that is disproportionate to areal coverage, and also highlight differences that exist across regions. A recent compilation of several long-term net carbon accumulation rate estimates from lakes worldwide, *Gudasz et al.* [2010] has shown a range variability in C accumulation rate between 2 and 90 g C m^{-2} yr^{-1}. There is clearly a need to better constrain these rates and the contribution of lakes to boreal C storage.

[4] There are two main challenges associated with lake C storage estimates at regional scale: 1) Deriving accurate estimates of whole-lake C storage for individual lakes, and 2) upscaling these estimates at the regional level. The former requires accurate determination of the total sediment volume as well as the sediment C content. Most studies to date have relied on either geometrical models based on lake area and depth [e.g., *Lehman*, 1975; *Campbell et al.*, 2000] or on few spatial estimates of sediment depth [*Pajunen*, 2000] when deriving the total sediment volume. In addition to large spatial heterogeneity generated by differential sediment deposition and focusing, which complicates the overall estimates of sediment C content [*Blais and Kalff*, 1995; *Rippey et al.*, 2008], lake basins often display a complex topology, which is difficult to capture with simple geometric models. The resulting C stock estimates are thus rather uncertain. The only study to date that has taken a different approach is that of *Pajunen* [2000], who estimated sediment volume based on the continuous profiles of sediment thickness along transects. Although a significant improvement, we argue that better models of sediment C stock will depend on the ability to perform more accurate measurements of sediment volumes which therefore require a more complete spatial coverage.

[5] The second major challenge in deriving reliable estimates of regional lake C stocks is related to the extrapolation of the actual measurements, usually performed on a limited number of lakes, to the ensemble of lakes within a region. This extrapolation must necessarily be informed by empirical models that allow to predict lake C stock or accumulation from easily obtainable lake properties, such as lake size or other morphometric features. Very few such models exist up-to-date. *Kortelainen et al.* [2004] developed a size-based model of total lake C stock for boreal lakes in Finland. Similarly, *Squires et al.* [2006], found significant correlations between storage and total basin depth in western Canada, while *Campbell et al.* [2000] did not find any significant limnological predictor of total C stock for lakes in boreal western Canada. These contrasting results indicate that either the lakes simply follow different regional patterns, or that the actual estimates of C stock may be biased in ways that obscure any consistent relationship.

[6] In this paper we address the two main challenges facing the estimation of regional lake C stock described above. On the one hand, we extend and improve on the approach taken by *Kortelainen et al.* [2004] on deriving total lake C stock based on detailed, three-dimensional maps of lake basins using a sub-bottom profiler [*Pajunen*, 2000; *Gilbert*, 2003]. We combined the resulting sediment volume estimates with Holocene core measurements of sediment C content to derive more robust estimates of whole-lake C stock. This approach was applied to a set of boreal lakes in the Eastmain River region of northern Québec, spanning a wide range in lake and watershed morphometry and environmental factors. We further derived empirical models that link total sediment C stock to both lake and watershed properties. Finally, we applied the resulting models to a 50,000 km^2 block of northern boreal landscape to derive a regional estimate of total C stock.

2. Methodology

2.1. Study Site and General Approach

[7] We investigated carbon storage in 13 boreal lakes of the James Bay region in northern Quebec (51–52°N; 75–76°N) in eastern Canada (Figure 1). The study was part of a larger project aiming to assess the net impact of a new reservoir creation (Eastmain-1 Reservoir) on the regional C budget [*Teodoru et al.*, 2012a]. The study area is located in boreal coniferous forest dominated by oligotrophic lakes, podzolic soils and extensive peatlands. Relatively homogeneous in geology (Precambrian bedrock of Canadian Shield with surficial quaternary deposits from the Wisconsinan glaciation) and topography (average altitude of 250 m a.s.l.), this boreal region is characterized by an annual average temperature of between 0 and −2.5°C, and annual precipitation varying from 600 to 1000 mm [*Teodoru et al.*, 2009]. The investigated lakes display a relatively large gradient of surface area, maximum water depth and catchment size. Due to remote nature of the region and low accessibility by road, these lakes were sampled by helicopter during two field campaigns in September 2007 and March 2008. The fall campaign was mainly focused on basin and sediment mapping, whereas the winter (March) campaign was dedicated to sediment coring.

[8] For mapping the three-dimensional distribution of sediment within each of the sampled lake, we used a triple-beam sub-bottom profiler capable of distinguishing simultaneously the sediment-water (208 kHz) and bedrock (24 Khz) interfaces coupled to a Differential Global Positioning System (DGPS) system, and collecting data at high frequency. The instrument (BSS+3 system, *Specialty Devices Inc.*) was mounted on a streamlined towfish and suspended from floats 0.4 m below the water surface on the side of the boat. Our spatial coverage consisted in a series of transects obtained by crisscrossing the lake about 7 km/h. For a full day, this generated on average about 121000 data points per lake

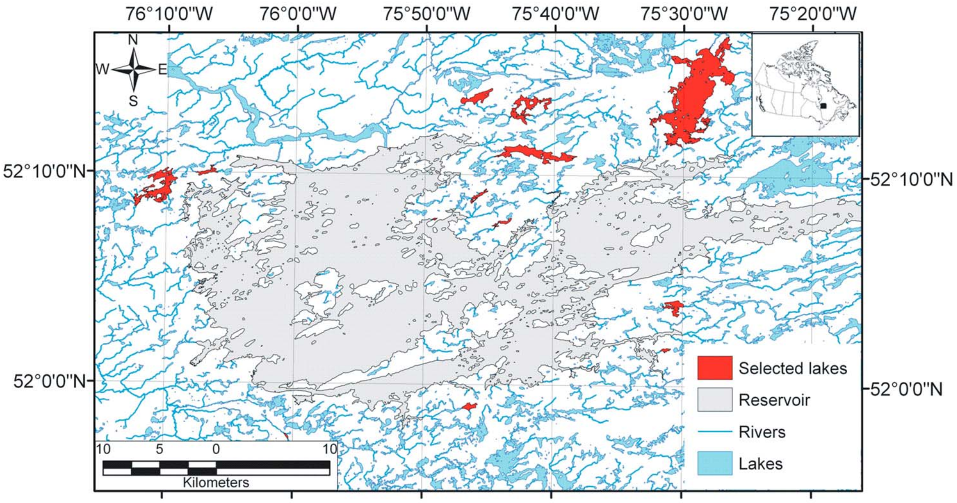

Figure 1. Map of location of 13 studied lakes in James Bay lowlands, Québec, Canada.

(between 1694 and 987673 data points) with the proximal points located at about 5 m distance from each other. Depending on the lake size, the sampling intensity varied between 40000 and 42300 data points per square kilometer. This resulted in an extensive spatial coverage, much higher than ever provided before in such studies. The depths of both, the sediment-water interface and of the original basin, were then interpolated (natural neighbor technique) over the entire lake surface to a 25 m^2 pixel size. The total sediment volume was then calculated by subtracting the two interpolated maps (Figure 2). All the geographic information analyses and manipulations were carried out using ARCGIS 9.3 (*ESRI*). The C content of the sediments and other chemical and physical properties were derived from long (Holocene) cores, which in combination with the estimated total sediment volume, were used to calculate lake-wide inorganic, organic and total C sediment storage for each lake.

2.2. Dissolved Nutrients Analyses

[9] Epilimnetic water samples taken from each lake at 1 m depth were used for nutrient and C analyses. Total phosphorus was determined spectrophotometrically following potassium persulphate digestion. For dissolved organic carbon (DOC) concentrations, water samples were filtered through 0.2 μm-filters and were measured in an OI-1010 Total Carbon Analyzer using wet persulphate oxidation.

2.3. Lake and Catchment Properties

[10] Lake and catchment properties (surface area, distribution of forest and peatlands within catchment, average altitude and mean slope, etc.) were calculated from digitized maps (National Topographic Data Base, scale 1:50,000, www.geogratis.cgdi.gc.ca/) using the hydrological and topographical extensions in ArcMap GIS 9.3. software. The dynamic ratio was calculated as the square root of the lake area divided by the mean depth of the lake.

2.4. Sediment Coring

[11] Sediment cores were obtained from the deepest point of each lake (or according to the vertical distribution obtained from mapping) using two different coring instrument: a) a long Livingstone corer [*Livingstone*, 1955] for

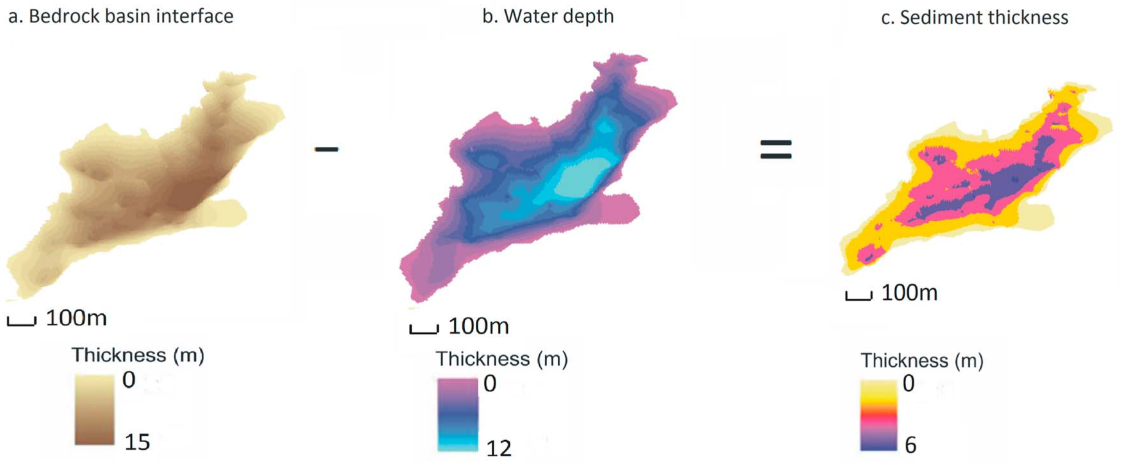

Figure 2. Three-dimensional maps of the basin of lake L34, showing (a) bedrock basin, (b) water depth, and (c) thickness of sediment.

Table 1. Lake Properties

Lake	Latitude (N)	Longitude (W)	Lake Area (km^2)	Catchment Area (km^2)	Lake Sediment Volume (m^3)	Average Water Depth (m)	Maximum Depth (m)	Residence Time (yr)	Average %C/%N Ratio	DOC mg L^{-1}	Carbon Stock (kg C m^{-2})
Mistumis	52° 09′ 42″	76° 10′ 51″	3.97	39.81	1991125	1.44	14.6	0.33	13.39	7.21	8.55
Em-320	52° 09′ 56″	76° 07′ 15″	0.47	4.54	416725	1.43	5.86	0.50	13.72	7.12	29.50
Labyrinthe	52° 13′ 34″	75° 42′ 49″	2.57	10.47	1583400	1.36	21.43	1.45	14.36	7.99	15.47
Clarkie	52° 13′ 40″	75° 29′ 22″	24.69	622.46	18228525	2.15	13.37	0.21	12.71	5.76	17.70
Brendan	52° 03′ 55″	75° 30′ 10″	1.06	6.39	1389325	3.23	15.88	1.05	13.15	5.24	22.74
Natel	52° 52′ 11″	75° 42′ 43″	3.86	24.28	3618500	4.13	25.86	1.40	13.48	6.10	15.60
Lake 2	52° 07′ 56″	75° 49′ 09″	0.04	1.06	26150	1.22	2.44	0.09	11.69	9.44	11.08
Lake 8	52° 07′ 55″	75° 43′ 26″	0.31	3.26	271175	2.23	9.66	0.42	13.21	6.17	33.19
Lake 11	52° 09′ 09″	75° 45′ 36″	0.37	4.31	376725	1.18	5.92	1.29	13.12	8.25	34.18
Lake 34	51° 59′ 05″	75° 46′ 01″	0.45	2.25	647050	3.59	11.63	1.60	13.22	7.86	36.48
Lake 60	52° 13′ 54″	75° 45′ 42″	1.38	9.54	2468025	5.28	16.23	1.48	12.38	5.84	27.14
Lake 66	51° 57′ 36″	76° 00′ 35″	0.07	4.97	146625	3.71	11.55	0.10	13.83	7.60	59.49
Lake 40	52° 01′ 46″	75° 31′ 25″	0.16	3.23	352050	4.10	13.00	0.39	12.04	4.72	54.11

sampling the entire Holocene sediment profile down to the bedrock; b) a gravity corer [*Glew and Last*, 2001] for a more detailed description of recent accumulation (the top 30 to 50 cm of sediment). The surface cores were sliced at each 0.5 cm for the top 5 cm and each 1 cm interval thereafter, whereas the Livingstone cores were sampled every 4 cm.

2.5. Sediment Carbon Contents

[12] The organic C content of lake sediment was calculated based on the loss on ignition (LOI) technique and mean C content of organic matter (OM) (modified from *Dean* [1974]). Dry bulk density was measured on 1 cm^3 subsamples taken at each 4 cm after drying in an oven for 16 h at 105°C. Subsamples were combusted at 550°C for 3 h to determine LOI, and the density of OM was calculated as the product between the bulk density and LOI. The resulting OM density was converted to C per unit volume assuming a constant average lake sediment C content of 50%. Although extensively used due to its simplicity and low cost [*Boyle*, 2004; *Heiri et al.*, 2001], the limitation of LOI technique is that it is based on the determination of the organic matter only, the actual carbon content being obtained by dividing the organic matter with an assumed C ratio (which in our case was 2) [*Dean*, 1974; *van Bellen et al.*, 2011].

[13] To validate the results of LOI technique, we used a CN elemental analyzer to measure directly the sediment C content. Although more accurate, the elemental technique is considerably more expensive to run. The comparison between both techniques performed on a subset of samples (7 per short core), resulted in a strong linear relationship between these two estimates ($r^2 = 0.68$, $p < 0.0001$) with LOI-based estimates somewhat more scattered, but with no evidence of a systematic bias. We thus used LOI technique on the remainder of the short core samples and on all of the samples from the long cores. Sediment C storage was calculated from the C content integrated over 1-m layers, and the total sediment C stock was calculated as the sum of the C in each of these layers. To apportion sediment mass into organic and inorganic mass, the LOI on 1 cm^3 was used to derive dry mass of organic matter content and was then integrated over 1-m layers. The balance of dry sediment in the 1 cm^3 volume was considered inorganic sediment mass and was also derived as dry inorganic sediment mass.

2.6. Radiocarbon Dating and Sediment Accumulation Rates

[14] Estimates of the regional long-term sediment accumulation rates were based on determinations of ^{14}C of bulk sediment organic C taken from the base of two long cores (lake 11 and Brendan lake), following the convention of *Stuvier and Polach* [1977]. Atomic Mass spectrometer (AMS) ^{14}C analyses of bulk sediment samples from two lakes were carried out at the radiochronology laboratories of Université Laval and University of California. All ages are expressed as calendar years before present (BP = before AD 1950).

2.7. Data Analysis

[15] Statistical analysis were carried out in JMP ©7 (*SAS institute*). Data were log transformed when necessary, to satisfy assumptions of homeocedasticity and/or normality.

3. Results and Discussion

[16] The Eastmain region is characterized by flat topography with an average slope of about 2.5 degrees and the lakes in the region are generally shallow (average mean depth of 2.7 m). We selected lakes to span a size-range of nearly two orders of magnitude (lake area between 0.04 and 25 km^2) with corresponding catchments varying between 1 and 622 km^2 (Table 1). Theoretical water residence time of the sampled lakes ranged from short (1 month) to intermediate (1.6 years). The lakes are oligo to mesotrophic (TP between 4.1 and 14.2 μg L^{-1}) and displayed a rather narrow DOC range (5–10 mg C L^{-1}, Table 1).

[17] Although the glacial history of the region is well constrained [*Dyke et al.*, 2003, 2004], we performed ^{14}C dating of Holocene core basal material from two lakes (L.11 and L. Brendan) located respectively south and north of the current Eastmain-1 reservoir (Figure 1). These two dates (7107 ± 47 and 7728 ± 28 cal. Years BP, respectively) are consistent with the deglaciation history of the region when, around 7.2 ka ^{14}C BP. (8 ka cal. BP), the Tyrell Sea retreated from the James Bay lowlands. We consequently used the average of these two dates (7418 cal. yr BP) as the beginning of lacustrine accumulation of organic matter for all study lakes of the region.

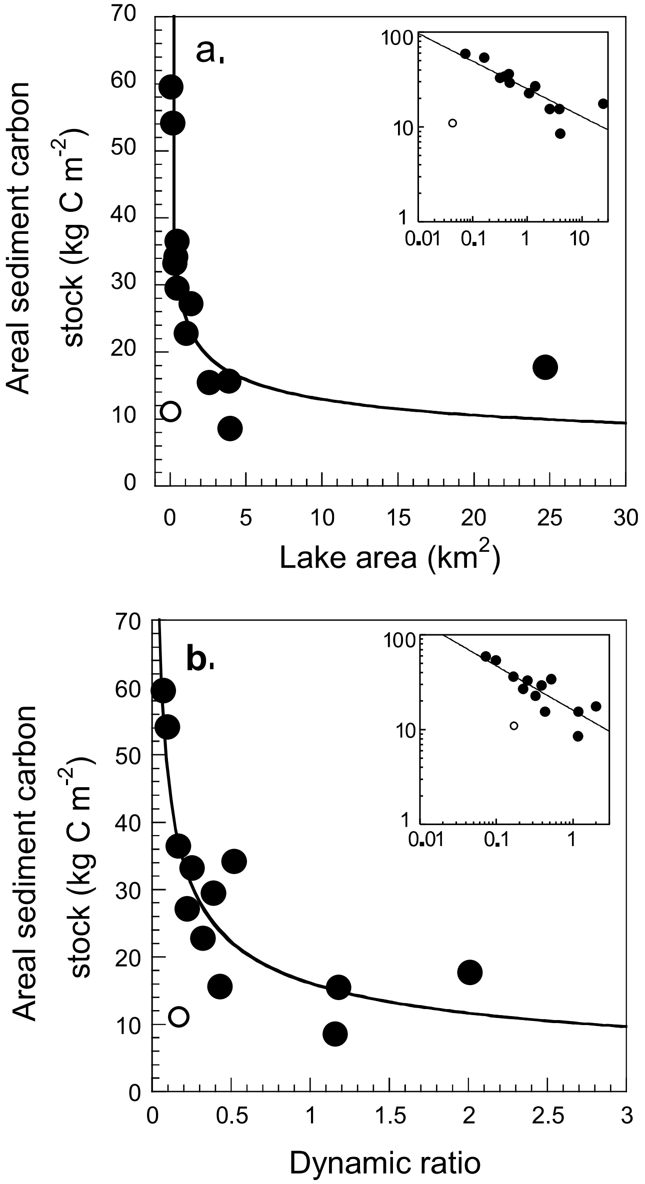

Figure 3. The relationship between sediment areal C stock (CS) and (a) lake area and (b) the dynamic ratio (√LA/mean water depth). The regression model for Figure 3a is $\mathrm{CS} = 23.23 \times \mathrm{LA}^{-0.29}$, $r^2 = 0.71$, $p < 0.0001$, $\mathrm{CS} = 893.86 \times \mathrm{DR}^{-0.555}$, $r^2 = 0.76$, $p < 0.001$. The open circle is Lake 2, which was not included in the regressions.

3.1. Areal Carbon Stocks and Accumulation Rates

[18] Areal organic carbon stocks varied between 8.6 and 59.9 kg C m^{-2} among our lakes which correspond to average annual accumulation rates of between 1.2 and 7.9 g C m^{-2} yr^{-1} (mean: 3.8 g C m^{-2} yr^{-1}). These rates are significantly lower than most reported values [e.g., *Mulholland and Elwood*, 1982; *Dean and Gorham*, 1998; *Boville et al.*, 1983; *Campbell et al.*, 2000; *Einsele et al.*, 2001; *Squires et al.*, 2006], but similar to those reported from Finnish and Greenland lakes [*Pajunen*, 2000; *Anderson et al.*, 2009; *Einola et al.*, 2011], and also close to *Stallard*'s [1998] estimate. A recent study of large scale patterns in C storage in European lakes [*Kastowski et al.*, 2011] also reported an overall average accumulation in the range of 5 g C m^{-2} yr^{-1}, based on the combination of lake-size distributions and empirical models of sediment C contents. Although these differences between studies can be due to true regional characteristics, it is also likely that our lower values are in part related to differences in methodology. Indeed, older estimates are based on sediment volumes derived by assuming a particular geometrical form (often ellipsoid) to describe the original and current bathymetry [*Lehman*, 1975; *Campbell et al.*, 2000]. In a companion paper (Y. T. Prairie et al., manuscript in preparation, 2012), we show that this assumption is rarely appropriate and generally overestimates true sediment volume in lakes. This latter analysis show that the ellipsoidal approximation, which is the most commonly used results in an average overestimation of sediment volume of 2.9 fold in our lakes. Similarly, applying the sedimentation rate obtained from the central core to the entire lake surface results in an overestimation of sediment volume of nearly fourfold. It is thus clear that the estimates of carbon stocks in sediments are highly dependent on accurate estimates of sediments volumes.

[19] Other possible reasons for the observed differences in carbon stock reported in the literature are not methodological but rather related to landscape characteristics such as catchment area, drainage ratio, vegetation cover [*Kortelainen et al.*, 2004], human impact on the landscape, temperature and latitude [*Kastowski et al.*, 2011], as well as the chemistry of the lake waters, including nitrogen and iron [*Kortelainen et al.*, 2004]. We explore some of these patterns in the sections below.

3.2. Predicting C Stocks and Accumulation From Lake Characteristics

3.2.1. Lake Area

[20] Because we focused on a relative small region that shares a common deglaciation history, the two metrics of carbon burial (areal C stocks and accumulation rates) are equivalent from a modeling point of view. In our data set, with the exception of Lake 2, there was a strong empirical negative power relationship between carbon stock and lake size (Figure 3a, $r^2 = 0.71$, $p = 0.0002$). Lake 2 is more akin to a shallow pond and departed from the general trends of all the other lakes. It was thus omitted from further analyses. As there are currently very few models attempting to predict long-term fate of the sediment carbon [*Kortelainen et al.*, 2004], this simple relationship represents a particularly useful tool for upscaling carbon burial at the whole landscape level (see section 3.3), as it is based entirely a lake feature (surface area) that can be easily be obtained. In a power law (i.e., double-logarithmic scales), a slope of -1 implies that the variables are inversely but proportionally related. Our slope is much shallower than negative unity (-0.29 ± 0.05), implying a highly decelerating function. Converted to an arithmetic scale, the relationship shows that most of the nonlinearity occurs for lakes smaller than 1 km^2. Above this threshold of lake size, carbon stocks do not vary by more than 10 kg C m^{-2}. This strong nonlinearity for small lakes (Figure 3a) is all the more significant because, in this boreal region, over 42% of the lakes are smaller than this threshold, a feature common to many areas of the world [*Downing et al.*, 2006]. Our predictive relationship is similar

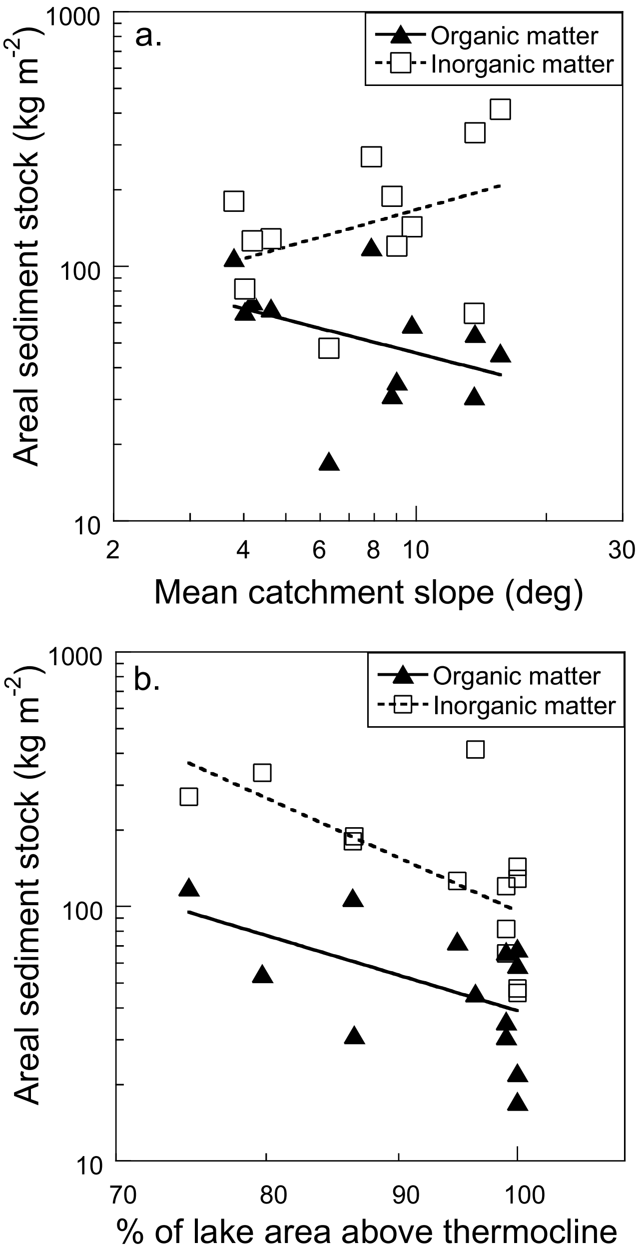

Figure 4. Relationships between inorganic and organic areal stock with (a) mean catchment slope and (b) proportion of sediment under the thermocline. The regression models are OM = 31.73 × $\text{Slope}^{-0.365}$ ($r^2 = 0.16$, $p = 0.19$) and IM = 54.75 × $\text{Slope}^{0.49}$, ($r^2 = 0.15$, $p = 0.22$) for Figure 4a and OM = 9E + 06 × $(\%\text{sed.})^{-2.66}$, ($r^2 = 0.23$, $p = 0.11$) and IM = 2E + 10 × $(\%\text{sed.})^{-4.07}$ ($r^2 = 0.40$, $p = 0.026$) for Figure 4b.

to that reported by *Kortelainen et al.* [2004] for Finnish lakes [$\sqrt{\text{Areal storage}} = 10.9 - 0.395 \times \ln \text{LA}\ (\text{m}^2)$], but also differs on several counts: First, our relationship predicts higher values for small lakes (<0.1 km^2) but lower values for larger systems. Second, our relationship is tighter ($r^2 = 0.71$) than in Finnish lakes ($r^2 = 0.47$). Again, differences in methodology can explain some of the differences but the spatial extent (and thus its landscape heterogeneity) of the Finnish study (whole of Finland) was much greater than the regional area covered by our lakes. The European data set of *Kastowski et al.* [2011] confirms the idea that small lakes have highly variable carbon mass accumulation rates (CMAR), and that above 1 km^2 lake size the variability in CMAR tends to decrease.

[21] Although the relationship of C accumulation with lake size is statistically convincing, it is less clear why larger lakes should exhibit lower C burial rates and C stocks (Figure 3a). In our view, the most likely explanations roughly fall under three categories: 1) Larger lakes tend to receive lower loads from their catchments, 2) large lakes process carbon differently from small lakes; and 3) lake size is simply an integrative surrogate for other important variables such as lake shape, which in turn influence burial efficiency. The worldwide study of large lakes by *Alin and Johnson* [2007] suggests that, at regional scales, burial efficiency of lakes is correlated to basin morphometry and other variables that can affect oxygen exposure of sinking particles, and suggests that shallower water columns are correlated with greater burial efficiency. Here we explore some of these alternatives, which are not mutually exclusive.

3.2.2. Carbon Loading

[22] We did not measure how much carbon these lakes received and therefore cannot test this hypothesis of differences in C loading directly. However, several lines of evidence suggest that differences in carbon loads are not the main driver of the size scaling of carbon accumulation in these boreal lakes. First, in such a uniform boreal landscape, areal carbon loads should be proportional to the catchment to lake area ratio (CA:LA) [*Squires et al.*, 2006], but this ratio and lake size were not significantly correlated ($p > 0.05$). C accumulation rate was not correlated to the CA:LA ratio, which is a rough proxy for potential C loading to lakes. Second, assuming that current differences in DOC concentrations among lakes were also similar through the Holocene, in-lake DOC concentrations should also reflect carbon loading rates. Here again, we found no relationship between DOC and sediment C stock ($r^2 = 0.0007$, $p = 0.93$) or with lake size ($r^2 = 0.26$, $p = 0.4$). Similarly, other proxies of organic carbon loading, such as catchment slope [*Rasmussen et al.*, 1989; *Sobek et al.*, 2007; *Teisserenc et al.*, 2010; *Kastowski et al.*, 2011] or the proportion of the catchment occupied by peatlands [*Molot and Dillon*, 1996; *Kortelainen et al.*, 2004; *Einola et al.*, 2011] bore no relationship with either lake size or sediment carbon stocks and accumulation rate. Further, a parallel study on C sedimentation carried out by our group showed that the downward POC flux was predominantly terrestrial and did not scale to size in these same lakes [*Teodoru et al.*, 2012b]. There is thus little compelling evidence to suggest that differences in carbon loading are the main drivers of the strong relationship between sediment C stock and lake size (Figure 4).

[23] The absence of strong patterns between allochthonous carbon loads and sediment C accumulation does not imply that watershed processes are completely decoupled from lake sediments either. When we partitioned the areal sediment mass into its organic and inorganic components, clearer trends emerged with catchment properties. Figure 4 shows how the slope of the catchment influences the organic and inorganic components in significant yet opposite ways (ANCOVA test for difference in slope, $p < 0.05$). For the inorganic fraction, there was a positive relationship with

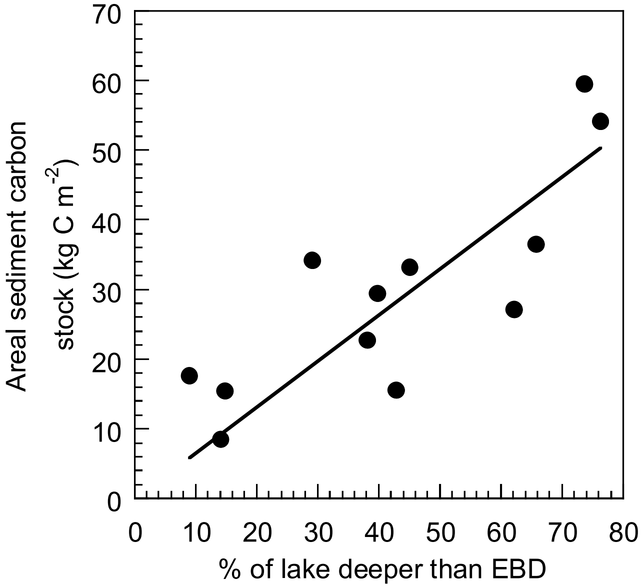

Figure 5. Relationship between sediment areal C stock and the fraction of the lake deeper than mud energy boundary depth (EBD) in lakes (orthogonal regression r^2 = 0.82, EBD = 1.37 + 66.17(% lake deeper than EBD).

catchment slope, which is consistent with higher erosional transport of inorganic material in steeper watersheds [*Walling*, 1983; *Dearing*, 1991; *de Vente et al.*, 2007]. In contrast, the organic fraction of the sediment mass was negatively related to catchment slope, which is consistent with current hypotheses as to the origin of sediment organic matter. Flat catchments typically sustain higher DOC exports because the soil waters are in greater contact with the organic-rich soil horizons [*D'Arcy and Carignan*, 1997] and high DOC of soils in flat region generally corresponds to thicker soils. If the organic sediment fraction originates largely through the flocculation of lake dissolved organic matter [*von Wachenfeldt and Tranvik*, 2008; *von Wachenfeldt et al.*, 2008], a negative pattern between the sedimentation of organic material and the watershed slope would ensue. From a mass balance perspective, this pathway of sediment organic matter production is likely operative. Of the two principal organic carbon sources, allochthonous organic carbon load largely dominates over primary production in these nutrient-poor lakes [*Brothers et al.*, 2012]. Whether or not the observed trend between OC burial and lake size (Figure 3) is the result of this complex interaction between the transport of DOC and sediment production processes will require further and more direct testing.

3.2.3. Lake Shape and Internal Carbon Processing

[24] Lake surface area alone does not fully characterize lake shape. In our data set, larger lakes tended to be much flatter (as measured by the dynamic ratio, $DR = \frac{\sqrt{LA}}{\bar{Z}}$) than small lakes. In fact, the dynamic ratio was even more closely associated to sediment carbon stock (and accumulation rate) than lake area (Figure 3b, r^2 = 0.76, $p < 0.0001$). This suggests that lake area may in fact act as a (useful) proxy for lake shape.

[25] Lake shape influences sediment processes [*Squires et al.*, 2006] and thus the rate of carbon accumulation in several ways. One hypothesis is that flat lakes tend to have more of their sediments exposed to warmer epilimnetic temperatures, thus favoring higher sediment decomposition rates [*Pace and Prairie*, 2005]. In this regard, the percentage of littoral sediment in our lakes (here defined as those within the epilimnion) was negatively related to lake area (r^2 = 0.43, p = 0.01) (not shown) and also positively related to DR (r^2 = 0.33, p = 0.05) (not shown), yet we did not find a significant trend between C accumulation and the fraction of the sediment surface within the epilimnion (r^2 = 0.31, $p > 0.05$). This would suggest that differences in the proportion of sediments potentially subjected to higher temperatures and therefore to higher decomposition of organic C do not explain the patterns of sedimentary C stocks observed across lakes.

[26] Alternatively, DR is closely related to the mean slope of the lake bottom and will thus determine the extent of sediment focusing [*Håkanson*, 1977, 1982; *Blais and Kalff*, 1995; *Johansson et al.*, 2007]. Sedimentation rate and focusing would be enhanced in smaller lakes with steeper bathymetry, and the efficiency with which sedimenting organic material is decomposed (either in transit or within the sediment pile) is generally inversely related to the downward flux [*Cornett and Rigler*, 1987; *Baines and Pace*, 1994; *Pace and Prairie*, 2005]. Accordingly, small lakes will have more localized and therefore enhanced sedimentation due of sediment focusing and should thus exhibit proportionately lower OC degradation and greater long-term permanent C burial rates.

[27] Last, lake shape could alter permanent carbon burial rate simply by influencing the total volume of sediments retained within the lake basin. *Rowan et al.* [1992] developed a model defining the depth above which sediment deposition does not occur (his mud Energy Boundary Depth, EBD) because the wave energy generated on a lake of a given exposure (surface area) is sufficient to maintain particles in suspension and eventually transport them out through the outflow. We calculated the EBD for our lakes from their model (empirical mud EBD = 2.685 × $E^{0.305}$ where E is "exposure" parameter) and used our precise bathymetry to obtain the fraction the lake surface greater than that boundary depth (we took lake area as the E parameter). This new variable, which we term the depositional capacity (DC), is very closely related to the dynamic ratio (DR) (r^2 = 0.92) and hence to the carbon burial metrics (accumulation and stocks). Figure 5 illustrates how this relationship is both linear and proportional. Since the intercept is not significantly different from zero (see caption of Figure 5), it also implies that little or no C will accumulate when none of its surface is deeper than the predicted mud EBD. This model also predicts that lakes, for which the entire surface can be deemed depositional (an unlikely situation), would accumulate carbon at an average of about 8.4 g m^{-2} yr^{-1}. This number implicitly assumes that all our lakes receive roughly the same areal loading. To further explore between loading and retention, we performed a multiple regression of carbon burial as a function of both DC and our coarse estimate of areal loading, the catchment to lake area ratio (CA:LA). Both terms are statistically highly significant and collectively explain 81% of the cross-lake variation in carbon burial. This result suggests that C loading does in fact play a significant role in the patterns of C accumulation in lakes, but that this role is

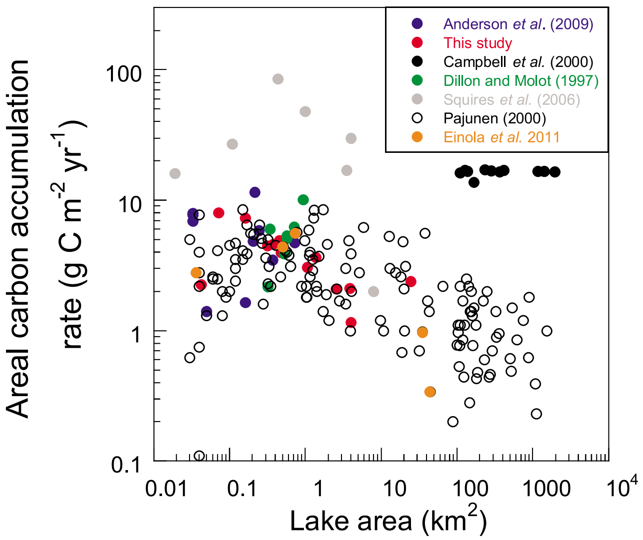

Figure 6. Regional patterns in the relationship between sediment areal C stock and lake size: Eastmain region, this study (red circles), Ontario lakes [*Dillon and Molot*, 1997] (green circles), Finland [*Pajunen*, 2000] (white circles) and [*Einola et al.*, 2011] (orange circles), Greenland [*Anderson et al.*, 2009] (blue circles), western Canadian lakes [*Campbell et al.*, 2000] (black circles) and [*Squires et al.*, 2006] (gray circles).

strongly modulated by both lake size and shape (Figures 3 and 5), which in turn determine the ability of lakes to retain the carbon that has been loaded. This in turn may explain why proxies of C loading on their own do not explain any significant portion of the variability in lake C stocks.

3.3. Comparison With Other Regions

[28] Our estimates of lake sediment C accumulation and total stocks are comparable to those reported for Finnish [*Pajunen*, 2000; *Kortelainen et al.*, 2004; *Einola et al.*, 2011] and Greenland lakes [*Anderson et al.*, 2009], but are considerably lower that reports for other boreal and temperate regions [*Mulholland and Elwood*, 1982; *Molot and Dillon*, 1996; *Campbell et al.*, 2000; *Squires et al.*, 2006], which range from 15 to over 90 g C m^{-2} yr^{-1}. Data from other studies also appear to fit the overall lake size scaling of sediment C stocks in boreal landscape (Figure 6) suggesting that this is not just a feature of the Eastmain region where we worked. This is encouraging given that lakes in these other regions can differ markedly in other respects (e.g., much longer water residence time in Greenland lakes, [*Anderson et al.*, 2009]). A striking feature of the comparative plot (Figure 6) is that the data from the Eastmain region exhibit a much tighter relationship with lake size than in other regions. We attribute this difference in part to the more accurate measurements of sediment volume and hence sediment C stock. It is also likely the result of the more homogeneous landscape of the relatively small Eastmain region we studied.

3.4. Scaling Up Lake C Burial at the Landscape Level

[29] Our results can be used to assess the relative importance of lake sediments C stocks at a regional scale. To this end, we carried out a GIS-based analysis of a large block of approximately 50,000 km^2 in the same region (51°00 N–52°45′N and 73°30′–77°00′W), for which we have obtained detailed information of lake abundance (excluding reservoirs) and size distribution (C. R. Teodoru et al., manuscript in preparation, 2012), in addition to forest and wetland coverage. Applying the relationship presented in Figure 3 to the size distribution of lakes (all lakes and ponds <1 km^2 were considered constant using lake 2 store value) in this block of territory yields a total potential sediment C accumulation of 24,500 t C yr^{-1} for the entire 50,000 km^2 landscape, and an average total weighted areal C stock of around 23 kg C m^{-2} (of lake area). This landscape-wide value is remarkably close to that obtained for Finnish lakes by *Kortelainen et al.* [2004] (19 kg C m^{-2} per lake area) and by *Einola et al.* [2011] (30 kg C m^{-2} per lake area), although it represents a somewhat longer period since the last glaciation (about 10 ka) [*Pajunen*, 2000]. The areal lake carbon stock represents over twice the average soil C stocks that have been measured for this same region (8.2 kg C m^{-2}) [*Paré et al.*, 2011], and around one fourth of the average C stocks in peatlands also determined for this same region (91 kg C m^{-2}) [*van Bellen et al.*, 2011].

[30] These ecosystem-specific C stock estimates can be scaled to the relative coverage of each type of system in the entire block, to derive a rough estimate of the contribution of each system to the total landscape C burial. Forest soils have by far the highest overall areal coverage, and therefore also the highest total contribution to C storage, in the order of 303 Tg C for the entire block. Peatlands, which cover less than 5.5% of the landscape, potentially store 245 Tg C, whereas lakes, which cover on average 15% of the total surface, contribute in the order of 185 Tg C. Thus, for this portion of the Canadian boreal biome, lakes rank third after forest soils and peatlands in terms of C storage, with lakes contributing on average 25% of the total landscape C storage. This situation is more akin to what has been described for Finland [*Kortelainen et al.*, 2004] than for Greenland [*Anderson et al.*, 2009] and Europe in general [*Kastowski et al.* 2011]. It should be noted that whereas the Eastmain region is average in terms of the lake coverage relative to other major boreal areas, it has an extremely high density of peatlands [*van Bellen et al.*, 2011], and therefore the above relative contribution of lakes to total C burial is a minimum value and likely to be significantly higher in other boreal regions with lower peatbog coverage.

[31] We can also compare our sediment C accumulation rates with the other major carbon fluxes occurring within these lakes. In a separate study we have quantified the annual CO$_2$ fluxes to the atmosphere from these same lakes [*Brothers et al.*, 2012], and our estimates of annual sediment C accumulation represent on average only 6% of C emitted from the same lakes to the atmosphere on an annual basis. This contrasts with the conclusions reported by *Tranvik et al.* [2009] for Swedish systems where the carbon burial in sediment represented nearly half of carbon emitted to the atmosphere. Clearly, the interplay between storage and evasion is complex and needs to be better understood.

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