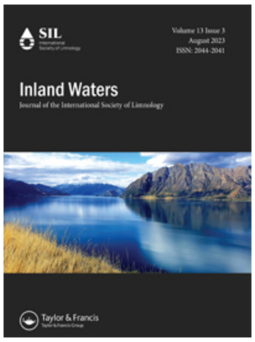

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Carbon and nutrient sequestration in small impoundments: a regional study with global implications

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ABSTRACT
The rate of sequestration of carbon, nitrogen, and phosphorus by lentic ecosystems informs both the global carbon budget and the remediation of eutrophication. Here we estimate carbon, nitrogen, and phosphorus burial in sediments of 34 lakes in Missouri, USA, and compare them to those found in other agricultural areas as well as to global estimates. Mean sediment accumulation rates varied by orders of magnitude among study regions, with the largest values (average 6 cm yr^{-1}) in impounded systems surrounded by intensive agriculture. Rates increased with the drainage ratio and decreased with the abundance of other surface water in the catchment (e.g., farm ponds). Average organic carbon burial differed by an order of magnitude among study regions (average 150–2100 g m^{-2} yr^{-1}) with differences related to the drainage ratio and eutrophication. Organic carbon burial was strongly correlated with burial rates of nitrogen and phosphorus. Comparisons with a diversity of global data show that extremely high rates of biogeochemical burial in many Midwestern USA impoundments are likely due to the details of agricultural cropping systems, landscape configuration, and soil characteristics.

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KEYWORDS
carbon; lakes; nitrogen; phosphorus; sediment; sequestration

Introduction

Understanding the drivers of climate change, water storage losses, and eutrophication requires quantitative knowledge of the sources and sinks of sediment, carbon (C), and nutrients (nitrogen and phosphorus; N and P) across diverse ecosystems (Canfield et al. 1982, Cole et al. 2007). Quantifying sediment and material deposition in lakes is also important to assess loss of freshwater storage on continents (Yao et al. 2023). Estimating lake nutrient budgets requires knowledge of sediment nutrient sequestration (e.g., Maavara et al. 2015). It is established that N and P are sequestered in lakes and reservoirs (hereafter called "lakes") and, it is also clear that lakes are effective C sinks (Cole et al. 2007, Maranger et al. 2018). Logically, C and N and P burial in lakes is correlated to some degree (Wang et al. 2021) because all are driven by the bulk of particulates delivered to the sediment pool. Knowledge of C and nutrient burial has been derived, often preliminarily, using estimates that essentially considered all lakes on the planet as equally unbiased estimators of gas evasion and C and nutrient burial (Downing 2009).

Better estimates of these important rates, however, can be calculated by determining the evasion and burial rates across the global range of lake types and integrating this knowledge into global evaluations (DelSontro et al. 2018). Because greenhouse gas flux estimation technology has advanced rapidly, science now has emission rates for thousands of waterbodies covering a diversity of ecosystem types (DelSontro et al. 2018, Beaulieu et al. 2019). Although equally important in understanding biospheric rates of lacustrine C and N and P flux, burial estimates are comparatively rare owing to the complexity of estimating whole-lake C and N and P sequestration. Accurate global estimation of the sequestration of these elements depends on how these rates vary among diverse lake and reservoir ecosystem types (e.g., Wilkinson et al. 2018).

Carbon and nutrient burial in small impoundments likely exceed rates in large reservoirs and natural lakes (Wilkinson et al. 2018), resulting in considerable influence on the global C cycle and eutrophication (Downing et al. 2008, Downing 2010, Taylor et al. 2019), especially because small lakes and impoundments cover substantial areas of the planet (Downing 2010). Currently, emphasis has shifted from studies of individual systems to landscape-level analyses of C storage, partly to quantify sources of variation among systems and upscale this

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important pool of material (Tranvik et al. 2009, Gilbert et al. 2021).

The purpose of this study was to expand on the work of Pittman et al. (2013) to document how morphology, hydrology, landscape features, and measurements of pelagic water quality influence sediment content and burial rates of organic C (OC) and N and P in mid-continent impoundments (Missouri, USA). These impoundments are in the transition zone between those intensively impacted by agriculture and those receiving moderate watershed inputs in forested regions (Downing et al. 2008, Jones et al. 2020) and therefore represent an extension to the impounded systems previously analyzed by others. Subsequently, a further aim was to compare sediment burial available from other midcontinent regions, which includes data from reservoirs in Ohio (Knoll et al. 2014), both natural lakes and reservoirs in Iowa (Downing et al. 2008), and natural lakes in Minnesota (Hobbs et al. 2013, Dietz et al. 2015). This broad characterization of landscape patterns in bioeochemical burial across midcontinent landscapes (USA) subsequently allows an important comparison of these rates to global patterns and provides pathways toward improving global estimates.

Methods

Study sites

We sampled 34 Missouri impoundments ranging over an order of magnitude in surface area (2.9–29.5 ha, mean 12.4 ha; Table 1). Impoundments were selected to represent the range of trophic state and land cover within this region (Fig. 1). Missouri straddles the temperate ecotone transition between western Great Plains and Eastern Forests and between the northern portion of the midcontinent region that was glaciated during the last ice-age and the southern region that was not (Fig. 1; Jones et al. 2020). As such, soil properties differ considerably along a north–south axis (Plains and Highlands). Prairies that originally dominated the Plains were converted to intensive agriculture well over a century ago. By contrast, the southern Highlands region is characterized by thin, permeable soils, greater relief, and a landscape dominated by forests and grasslands. This contrast has a strong influence on trophic state, and conditions span much of the global range for P and other common water quality metrics (e.g., N, suspended solids, dissolved OC, turbidity; Jones et al. 2020).

Table 1. Physical and hydrologic characteristics of Missouri lakes and reservoirs analyzed in this study.

Lake name	Lake area (ha)	Watershed area (ha)	Mean depth (m)	Annual runoff (cm)	Age at analysis (yr)
Amarugia Highlands W	22	393	2.4	19	26
Austin	9	102	2.1	36	55
Ben Branch	18	70	3.9	26	29
Bennett	19	259	3.8	20	14
Bucklin City	6	119	2.3	16	76
Clarence West	8	122	2.3	18	57
Edina City	18	295	3.0	15	57
Ella Ewing	3	156	1.7	15	44
Fayette	25	509	2.5	21	52
Green City	24	390	1.5	15	39
Greenly Farms	7	98	1.7	17	36
Hazel Hill	29	670	2.9	20	24
Higbee City	5	45	3.4	20	50
Jamesport Comm	12	120	1.6	14	57
Lancaster City	17	306	2.3	14	37
Lawson City	10	91	1.5	16	49
Lick Creek	6	55	1.7	21	41
Lincoln Lake	13	404	5.3	22	48
Macs/Ziske	10	146	1.8	36	48
Monroe	17	269	2.4	18	76
Nodaway County	30	276	4.2	11	47
Pine Ridge	10	123	1.5	18	25
Pinewoods	12	105	1.9	43	35
Prairie Home 2	6	69	2.3	22	16
Ray County	10	127	1.5	17	59
Savannah City	8	239	2.6	13	87
Sears Community	7	83	2.5	19	50
Tri-City Community	12	152	1.9	21	56
Vandalia	9	206	1.6	21	57
Walter	3	81	1.5	22	53
Whitesell	5	58	1.5	23	53
Whiteside	9	101	3.1	21	33
Williams	10	855	3.5	16	44
Worth County	8	97	2.0	11	56

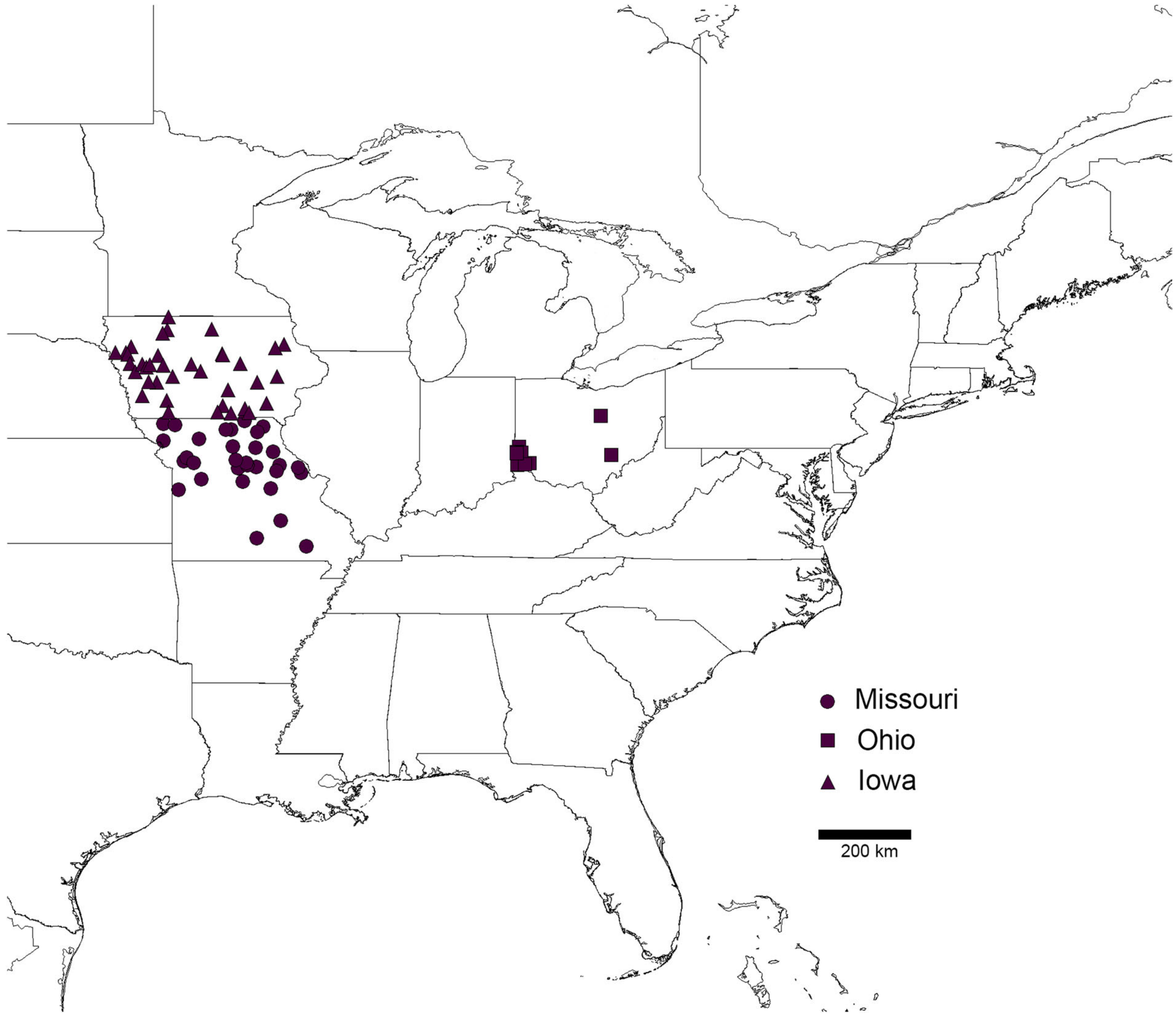

Figure 1. Locations of Missouri, Ohio, and Iowa lakes analyzed in the continental United States.

Sampling was conducted during summer 2013. The 4 reservoirs studied by Pittman et al. (2013) were of similar size (6.1–24.5 ha, mean 11 ha; Table 1), and that dataset was included to increase the sample size to 34. All collection, analytical methods, and equipment followed Pittman et al. (2013). Briefly, multiple sediment cores were taken along perpendicular transects across each basin with multiple cores taken at some sites (discussed later). OC and P concentrations in the sediments were measured every 5–10 cm in each core. Sediment thickness was measured (Brenner et al. 1998) by forcing metal coring rods as far as possible through sediments. Phosphorus in sediment was determined after acid extraction and total P was determined using a Liberty RL Sequential ICP-AES analyzer (Varian Inc., Palo Alto, CA, USA) after methods described in EPA Method 200.7 (Martin et al. 1994). Our sediment OC estimates (sedOC) were analyzed at several depths in core samples as loss on ignition (LOI) at 550 °C following standard methods of estimating sedOC (e.g., Dean 1974, Dean and Gorham 1976, Heiri et al. 2001, Downing et al. 2008). LOI divided by 2.13 was used as a reasonable approximation of sedOC content because analyses performed in an adjacent region with similar water column cation chemistry have indicated that such estimates are comparable in precision and accuracy to other methods (Downing et al. 2008). Further mention of "sedOC" and "sediment OC burial" will refer to OC approximations estimated by LOI. Total C and N concentrations in the sediment were also determined by dry combustion at 950 °C using a LECO Tru-Spec C/N analyzer (LECO Corp.; St. Joseph, MI, USA) based on methods of Nelson and Sommers (1996). Results are expressed as mg OC per gram dry sediment. Dry bulk density (DryBD) of the sediment (g dry mass [DM] cm^{-3}) was determined after Downing et al. (2008). Given DryBD, measures of sediment volume deposited over the lifetime of the impoundments and estimates of sedOC deposited per unit dry sediment mass (DM), the OC deposition rate can be calculated for each waterbody (see Downing et al. 2008). OC deposition rate over the life of the reservoirs was estimated as the sediment mass deposition rate (the product of sediment volume deposited and DryBD as g DM cm^{-3}) multiplied by the sedOC as estimated by LOI (mg DM g^{-1} of sediment).

Following methodology suggested by Pittman et al. (2013), a core was collected at the center point along the longitudinal midline and at the mean depth. From 3 to 11 additional cores were collected along the longitudinal axis to characterize concentrations and account for spatial variation. An example of the distribution of core samples shows the number of core samples taken in each lake (Supplemental Fig. S1, Supplemental Table S1). Sampling effort was scaled based on surface area (4–12 cores from individual reservoirs), with an average sampling density of 0.6 cores per ha (from 0.4 to 1.4 cores per ha); 215 total core samples were collected and 597 sediment segments (5 or 10 cm in length) were analyzed. Included were data from 146 sediment cores consisting of 520 segments from Pittman et al. (2013), totaling 361 cores and 1117 sediment segments. Core depth ranged from 5 to 43.5 cm in this study and from 5 to 54.5 cm in Pittman (2011). Soft sediment thickness in this study ranged from 10 to 270 cm. The sediment accumulation rate (SedAR) was calculated as the geometric mean of the soft sediment thickness divided by reservoir age in years (14–87 years, arithmetic mean of 47 years; Ritchie 1989, Pittman et al. 2013; Table 1).

Sediment OC, total N, and total P values are expressed as percent DM of sediment. Consistent with the goal of estimating recent deposition in these reservoirs, data from the 0–5 cm segment of the cores are the focus of most analyses; however, some comparisons are made with core averages. Sediment OC content and N and P accumulation rates for the 34 reservoirs were determined by multiplying the weighted mean of the SedAR by reservoir mean dry bulk density (Ritchie 1989, Pittman et al. 2013). Estimates of OC burial should be considered "net" sequestration because they are integrated over several years.

Land cover determination described in Jones et al. (2009) included the following categories: forest, cropland, grassland, urban, and surface water (including the combined area of farm ponds) in the catchment. Following Knoll et al. (2014), we combined cropland and grassland to represent agricultural land use in the Missouri catchments (%AG), but these categories were treated separately in some analyses. In Ohio, cropland dominated agricultural land cover. Values were expressed as percent of catchment area. Morphology data include the drainage ratio (watershed area [WA]/reservoir surface area [SA]). Mean runoff (catchment water export) was interpolated from data in the Missouri Water Atlas (Missouri Department of Natural Resources 1987). Annual runoff ranges 4-fold along a northwest to southeast axis in the state (11 to 43 cm, respectively; Table 1).

Water chemistry and algal chlorophyll data were estimated as averages from the long-term study of Missouri reservoirs (Table 2; Jones et al. 2020). Reservoirs occur in erosional topography and impound the lotic flow that created the valley (Jones et al. 2020); as such, many have high levels of suspended solids from allochthonous material delivered from the watershed and internal resuspension. Our measurements of these materials in the water column include the nonvolatile fraction (NVSS; mg L^{-1}) and filterable seston (fTSS; mg L^{-1}; Knowlton and Jones 2000). This measurement includes fine clay-sized materials and small organic matter, which can exceed the weight of NVSS in some cases (Jones et al. 2020). Nonalgal seston (NAS; mg L^{-1}), the sum of NVSS and fTSS, provides the best estimate of mineral seston in this analysis (Jones et al. 2020; Table 2 [full dataset available on request]).

Data analyses, including correlation and regression (simple and stepwise) were performed on $\log_{10}$-transformed data or logit transformation for percentages, unless otherwise stated. Acceptable significance for interpretations of correlations was set at a p value of <0.01, and the analyses were based on 34 Missouri reservoirs, unless otherwise stated. In several cases least squares regression was used to identify variables accounting for cross-system patterns and not for prediction; these models were described but not shown. Coefficient of variation (CV) was used to express uncertainty. Means are geometric calculations, unless otherwise stated. Statistical analyses were conducted using SPSS (version 26).

Results and discussion

Sediment accumulation rate

DryBD averaged 0.56 g cm^{-3} among the 34 Missouri reservoirs (core average) and ranged from 0.32 to 0.84 g cm^{-3}. Values in the surface segment were about 25% less than the entire core, which is the pattern reported for Ohio reservoirs (Knoll et al. 2014). Average DryBD values were similar in Missouri and Ohio (median 0.52 g cm^{-3}, range 0.31–0.65, $n = 13$), which matched the minimum measured in Iowa reservoirs (0.52 g cm^{-3}; Downing et al. 2008). Sediment OC content averaged 24.7 g kg^{-1} dry weight (SD = 5.8, $n = 34$),

Table 2. Limnological characteristics of Missouri lakes and reservoirs analyzed in this study.

Lake name	Total P (μg L^{-1})	Total N (μg L^{-1})	Chlorophyll *a* (μg L^{-1})	Nonvolatile suspended solids (mg L^{-1})	Volatile suspended solids (mg L^{-1})	Sediment accumulation rate (cm yr^{-1})	Organic C burial (g m^{-2} yr^{-1})	N burial (g m^{-2} yr^{-1})	P burial (g m^{-2} yr^{-1})
Amarugia Highlands	43	612	10	3.8	2.1	1.53	207	21.9	8.3
Austin	22	625	10	0.9	3.3	0.43	105	10.6	1.3
Ben Branch	20	648	10	0.6	2.0	0.66	104	11.0	2.1
Bennett	54	812	19	3.9	4.0	0.96	95	8.0	2.7
Bucklin City	114	1621	26	6.5	6.8	0.47	56	6.1	2.0
Clarence West	50	811	19	3.9	4.1	1.46	212	24.4	5.3
Edina City	75	1576	29	7.2	6.0	1.46	191	22.2	5.7
Ella Ewing	74	1112	43	2.3	6.1	1.85	264	29.2	7.6
Fayette	50	690	21	4.3	4.8	2.47	213	26.7	9.9
Green City	73	1123	28	5.7	5.4	1.49	210	24.5	7.5
Greenly Farms	117	1717	81	4.5	9.7	1.21	178	20.3	6.2
Hazel Hill	51	998	30	2.9	5.4	1.70	249	24.3	10.3
Higbee City	25	634	8	1.0	2.1	0.40	49	5.5	1.1
Jamesport Comm	133	2077	115	2.8	14.7	0.97	170	18.2	3.1
Lancaster City	75	967	34	3.3	5.7	0.70	131	13.1	2.8
Lawson City	35	951	22	2.7	4.6	1.50	176	19.5	3.8
Lick Creek	20	547	6	0.8	1.7	1.64	241	26.9	4.9
Lincoln Lake	13	370	4	0.9	1.3	1.02	125	13.9	2.4
Macs/Ziske	14	440	5	0.7	1.2	0.39	63	6.2	0.9
Monroe	86	1318	45	8.3	7.6	1.58	191	24.4	6.7
Nodaway County	50	1083	28	4.6	4.9	0.89	143	15.9	4.1
Pine Ridge	58	1074	27	1.8	5.2	0.76	120	13.4	2.6
Pinewoods	21	537	9	0.6	3.0	0.55	135	12.1	2.0
Prairie Home 2	49	817	15	9.0	3.7	1.71	295	26.2	5.0
Ray County	160	1940	111	3.8	15.6	0.56	83	8.4	2.1
Savannah City	42	887	21	3.0	3.9	1.96	250	22.8	8.2
Sears Community	174	1349	64	7.5	9.8	1.23	120	13.3	4.4
Tri-City Community	52	843	20	2.9	4.0	0.77	94	11.1	2.4
Vandalia	88	1284	47	4.9	8.2	0.91	142	16.9	3.8
Walter	9	365	2	0.4	0.7	0.77	114	11.3	1.6
Whitesell	19	620	9	1.4	2.1	0.76	99	10.5	1.7
Whiteside	20	717	8	0.5	1.7	0.86	211	22.1	5.1
Williams	127	1032	66	7.5	9.7	3.38	536	48.9	17.7
Worth County	62	1209	24	2.6	4.8	1.57	260	29.2	6.2

similar to values measured in Ohio (range 17.1–35.0; Knoll et al. 2014) and lower than the average of direct measurements in Iowa reservoirs (41.5 g kg^{-1} dry weight, range 3.6–91.5; Downing et al. 2008). The DryBD and the C and N and P concentrations in the sediments are available (Supplemental Table S2).

In Missouri, SedAR varied by an order of magnitude, spanning from 0.39 to 3.38 cm yr^{-1} (Table 2), with only 2 reservoirs with values >2 cm yr^{-1}. These values fit within the range from other Midwestern lakes and reservoirs, but the geometric mean of 1.04 cm yr^{-1} is about two-thirds the value of the Ohio study (1.53 cm yr^{-1}; Knoll et al. 2014), similar to the average among natural lakes in Iowa (1.19 cm yr^{-1}, $n = 7$; Downing et al. 2008), and triple the median burial rate in Minnesota lakes (Dietz et al. 2015). However, the Missouri SedAR values were <25% of the average in Iowa lakes and reservoirs (5.94 cm yr^{-1}, $n = 40$; Downing et al. 2008). This comparison shows considerable regional variation in SedAR and highlights that the values reported from Iowa reservoirs, a region of extraordinarily intense production agriculture, can be extreme (Downing et al. 2008).

In Missouri, SedAR was positively related to the drainage ratio ($r = 0.49$, $n = 34$; Fig. 2a) and negatively related to the percentage of watershed area comprised of water (%surface water; $r = -0.49$, $n = 34$; Fig. 2b). Regression analysis (Table 3) suggests that an increase in the drainage ratio from 11 to 20 (the interquartile range; Table 1) would increase SedAR from 0.90 to 1.18 cm yr^{-1} (31%), while an increase in %surface water from 6 to 11.4% would be related to a decrease in SedAR from 1.3 to 0.8 cm yr^{-1} (36%). Similarities among these opposite outcomes are a consequence of multicollinearity; strong negative correlations exist between %surface water and the drainage ratio ($r = -0.85$, $n = 34$). In a management scenario, an alteration to the drainage ratio by raising the dam to increase lake surface area (and depth) is not universally feasible. This analysis, however, suggests a ∼5% increase in surface water by establishing additional ponds in the catchment would decrease SedAR by more than one-third; consequently, pond construction is used extensively in this region for water quality mitigation (Minnesota Pollution Control Agency 2023).

High drainage ratios drive high sediment accumulation rates because sediment and nutrient loads increase with the land area contributing input to reservoirs and other waterbodies, so erosion and nutrient dissolution

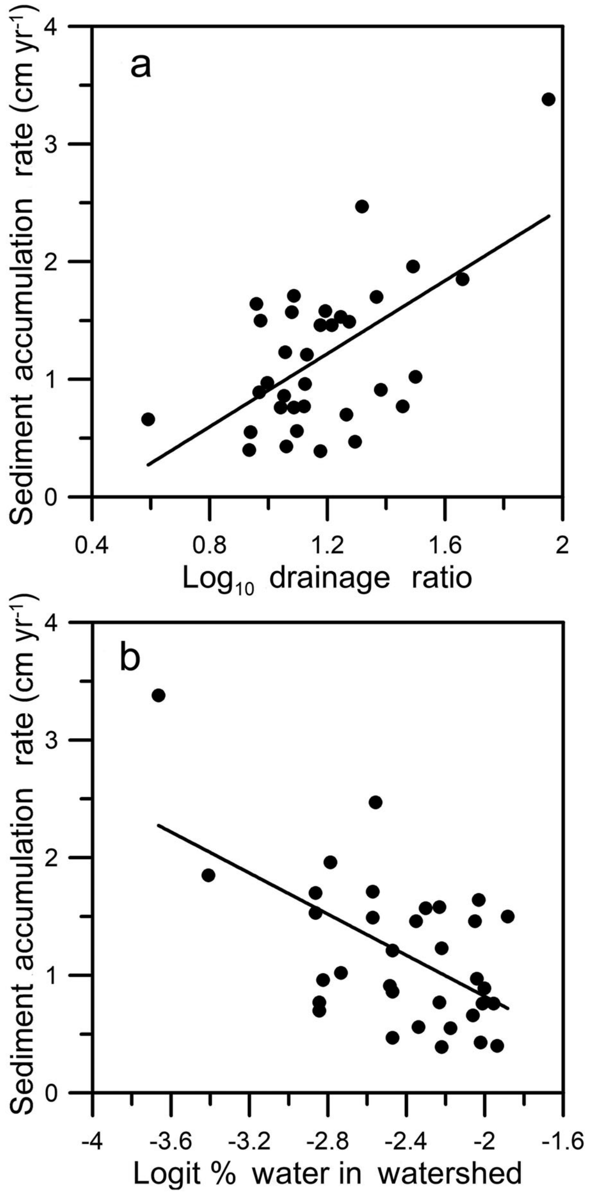

Figure 2. Relationship of the sediment accumulation rate in Missouri lakes and reservoirs showing correlations with (a) the drainage ratio (watershed area:lake area) and (b) the percentage of the watershed composed of other waterbodies such as ponds and wetlands.

Table 3. Results of regression analyses to determine the effect of various lake and watershed variables on the $\log_{10}$ of the sediment accumulation rate (cm yr^{-1}) in 34 Missouri, USA, lakes. The 2 top models are shown, based on the size of the coefficient of determination (r^2). SE = standard error of the estimate.

Intercept	$\log_{10}$ (Watershed area/lake area)	Logit %surface water in watershed	r^2	SE
−0.534	0.466	—	0.239	0.206
−0.645	—	−0.273	0.241	0.206

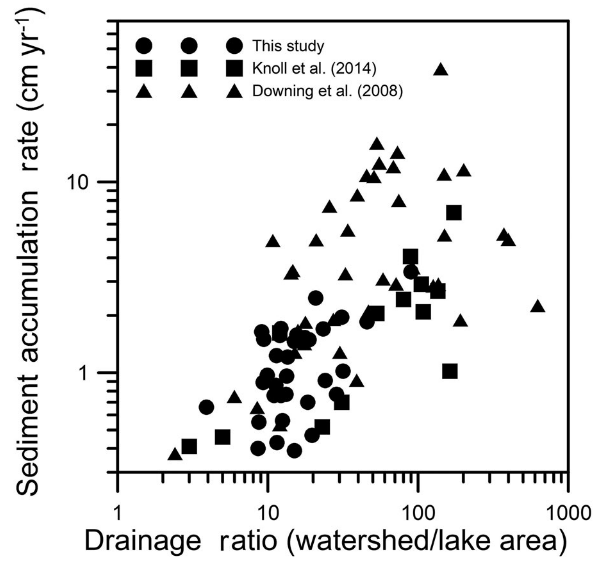

Figure 3. The relationship between the sediment accumulation rate and the drainage ratio for lakes in Missouri compared to those in Ohio and Iowa. This study = Missouri (circles); Knoll et al. (2014) = Ohio (squares); Downing et al. (2008) = Iowa (triangles).

are extensive (Harrison et al. 2009, Powers et al. 2015). The Iowa reservoirs likely have the highest rates because of intensive maize production agriculture requiring extreme rates of tillage (Thaler et al. 2021). Further, in the Missouri watersheds, plentiful water in landscapes creates a network of ponds in the uplands that can play a vital role in decreasing downstream transport of nutrients and sediments, and thus likely decreases C and N and P sequestration (Céréghino et al. 2014).

The percentage of the watershed made up of open water, other than the lake (%Surface water), was the only land cover feature accounting for cross-system variation in SedAR in this dataset. It represents the available quantification of small farm ponds in the agricultural catchments of the study reservoirs. Decades ago, ponds of <1 ha were established to control erosion and provide farmstead water (Barnickol and Campbell 1952, Compton 1952), with numbers increasing over time (Downing et al. 2006). Small ponds are depositional features in larger catchments and are known to trap sediment and influence the sediment budgets of landscapes (Verstraeten and Poesen 2000, Smith et al. 2002, Rogers et al. 2022), especially important because wetlands in these catchments may have been selectively drained (Heathcote and Downing 2012). These ponds slow the loss of storage capacity in larger, often multipurpose, reservoirs (deNoyelles and Kastens 2016). In one study reservoir, sedimentation decreased by over half as ponds in the catchment increased (Berg et al.

2016), which is consistent with the landscape-level signal of SedAR declining with %surface water in Missouri.

The sediment accumulation rate was positively correlated with both NVSS and NAS in epilimnetic samples from the Missouri reservoirs ($r = 0.51$ and 0.49, respectively, $n = 34$), which follows that sedimentation increases with mineral turbidity in the water column. This finding is consistent with both sediment delivery from the watershed and internal processes, such as shoreline erosion (Jones and Knowlton 2005), which is substantial in newly formed impoundments as wind and wave action resculpt the formerly terrestrial landscape (Baxter 1977, Hamilton and Mitchell 1988).

The relationship between SedAR and drainage ratio was also significant in the combined dataset from the 3 states and accounted for 40% of among-reservoir variation (Fig. 3). Sediment accumulation tends to increase with drainage ratios because more erosion accumulates when larger land areas provide runoff (Harrison et al. 2009, Powers et al. 2015). Sediment deposition in the Iowa lakes is often much greater than in Missouri or Ohio because of the extremely large drainage ratios. The regional pattern (using regression), however, underpredicts median SedAR among Iowa reservoirs by ~10% (0.37 cm yr^{-1}, $n = 33$), while overpredicting median values in Missouri and Ohio by 20% and 50%, respectively (−0.20 cm yr^{-1}, $n = 34$ and −1.05 cm yr^{-1}, $n = 13$). These comparisons suggest substantial within-region differences in sediment delivery, which limits the ability to predict SedAR based on landform morphology across the midcontinent region. Cropping systems (tillage, cover crops) can alter erosional soil loss by nearly 4-fold (Chowaniak et al. 2020, Rogers et al. 2022), but regional-scale data are not available to determine this influence on cross-system or temporal patterns. These results, however, support that intensive agriculture in Iowa results in greater sedimentation than elsewhere in the Midwest and indicate that type of land disturbance is relevant to the overall rate of OC sequestration.

Although speculative, we postulate that SedAR and reservoir storage loss will increase radically with climate change. Deposition of autochthonous OC will likely increase because of increased eutrophication (Beaulieu et al. 2019), which will almost certainly double over the next century. Allochthonous sediment delivery will also likely increase substantially because of changes in temperature and storminess over the next several decades (Jeppesen et al. 2009, Downing 2014, Sinha et al. 2017). Climate change and eutrophication impacts on reservoirs such as these will result in large increases in both atmospheric- and landscape-derived C and N and P sequestered in lakes and reservoirs.

The negative relationship between SedAR and SA from Downing et al. (2008) was not significant at the regional scale ($n = 80$), or for Missouri and Ohio, individually or combined, likely because of the narrow range of lake SAs examined in Missouri and Ohio. In this combined dataset, watershed area (WA) accounted for 48% of variation in drainage ratio.

Sediment chemistry

Sediment OC and N and P averaged 2.94%, 0.32%, and 0.07%, respectively, in the surface segment of Missouri reservoirs, comparing closely with findings in Ohio (2.29%, 0.30%, and 0.09%, respectively; Knoll et al. 2014). Average %OC values in both studies were >1.9%, the value reported by Ritchie (1989) for small impoundments. By comparison, OC was 4.0% among all waterbodies in the Iowa study and about 4.1% in the reservoirs with direct measurements (Downing et al. 2008), further demonstrating higher OC sediments in the highly eutrophic impoundments in Iowa (Jones and Bachmann 1976, Downing et al. 2008). Because of the post-glacial history of Iowa and the prominence of wetlands across that region (now drained; Heathcote and Downing 2012), Iowa soils are particularly rich in OC (Guo et al. 2006) because they originated as hydric soils. In a global analysis of agricultural soil C, Georgiou et al. (2022) found that mineral-associated soil C can vary >1000-fold.

As in Ohio, sedOC and N and P concentrations were similar among Missouri reservoirs (CVs from 0.27 to 0.29, $n = 34$). The %OC in sediments and %N were strongly correlated in both studies ($r = 0.96$ in Missouri and 0.82 in Ohio), but %P was not correlated with the other elements in either study, reflecting differences in biogeochemistry among these elements (Maranger et al. 2018). In Missouri, all 3 elements were negatively correlated with DryBD ($r = -0.48$, −0.56, and −0.44 for %OC, %N, and %P, respectively, $n = 34$).

In Missouri, both %OC and %N were negatively correlated with NAS concentrations in epilimnetic samples ($r = -0.06$ and −0.52, respectively), as well as both the particulate and filterable fractions of this metric (NVSS and fTSS, $r = -0.46$ to −0.55, depending on the element and fraction). The implication is that %OC and %N content of sediment is reduced (diluted) by sedimentation of mineral turbidity from the water column (Canfield et al. 1982). Both elements decreased with SedAR ($r = -0.34$ and −0.36 for %OC and %N, respectively; $p < 0.05$, $n = 34$) and with DryBD ($r = -0.49$ and −0.56, respectively, $n = 34$). These findings are consistent with the conclusion of Downing et al. (2008) that impoundments with low allochthonous input have the highest %OC content.

Across all 34 Missouri lakes, mineral turbidity in epilimnetic samples increased with the percentage of agricultural cropland in the watershed (%crop) and decreased with depth (Jones and Knowlton 2005), and in this subset of reservoirs, NVSS in the epilimnion was strongly correlated with %AG ($r = 0.61$, $n = 34$). In multiple regression, 45% of among-system variation in both %OC and %N were accounted for by average NAS in the epilimnion and %AG in the catchment (negative and positive coefficients, respectively; $n = 34$).

The percentage of P in the sediments (%P) was positively correlated with WA, %AG, and %crop and negatively correlated with runoff and %forest. By contrast, in Ohio the relation between %AG and %P was negative, even when 2 small urban reservoirs were removed from the analysis (Knoll et al. 2014). The positive pattern in Missouri reservoirs between %P and %AG was driven by %crop because the relation with %grassland was not significant. These correlations indicate an increase in %P with WA, which serves as a measure of potential delivery to the impoundment. The patterns with agriculture and forest are consistent with these landscape-level features of the catchment accounting for variation in nutrients and suspended sediment in epilimnetic samples (Jones and Knowlton 2005, Jones et al. 2009).

Evidence suggests chemical changes in the sediment of Missouri reservoirs over time, or that deposition rates are increasing over time, because the ratio of %OC, %N, and %P in the top segment of sediment (5 cm) is greater than the weighted average across all cores and depths. On average, surface sediments contained 22% more OC (range 0.9–1.6%), 26% more N (range 0.9–1.7%), and 12% more P (range 0.9–1.6%) than the core average. Ratios of %OC and %N across reservoirs were strongly correlated ($r = 0.92$, $n = 34$) and somewhat weaker with P ($r = 0.64$ with OC and $r = 0.61$ with N, $n = 34$). About 10% of the surface-core ratios were at or below unity, suggesting greater sediment uniformity in some impoundments, particularly for P. The measured decreases in both %OC and %N in sediment were consistent with decadal declines in other lake studies (Gälman et al. 2008). Mineralization processes in the sediments (for N this would include denitrification) likely account for the decrease in these elements in lake cores (Gardner et al. 1987, Gudasz et al. 2010).

Carbon, phosphorus, and nitrogen deposition rates

Burial rates for OC, N, and P in Missouri averaged 151, 16, and 4 g m^{-2} yr^{-1}, respectively (Table 2), values uniformly lower than found in Ohio reservoirs (166, 22, and 7 g m^{-2} yr^{-1}, respectively; Knoll et al. 2014). Minimum values in the 2 studies, however, were similar (49 vs. 47 g m^{-2} yr^{-1} for OC, 5 vs. 6 g m^{-2} yr^{-1} for N, and 0.9 vs. 1.0 g m^{-2} yr^{-1}, Missouri and Ohio, respectively), while maximum values were from 50% to 170% larger in Ohio. Mendonça et al. (2017) reported a global median OC burial of 291 g m^{-2} yr^{-1}, about double the averages for Missouri and Ohio. By comparison, OC burial averaged 2080 g m^{-2} yr^{-1} among the 22 Iowa reservoirs with direct measurements (Downing et al. 2008), which exceeds global median by an order of magnitude, likely because the Iowa systems have extremely high SedAR (average 5.95 cm y^{-1}) coupled with high sedOC (average 4.8%; JAD, pers. commun.). Carbon burial rates in reservoirs seem particularly sensitive to differences among landscapes.

Collectively, drainage ratio explained about a third of the cross-system variation in OC and N burial rates in Missouri and Ohio and 45% of P burial (Fig. 4). This comparison supports the finding of Knoll et al. (2014) that hydrogeomorphic features, like drainage ratio, largely influence burial rates. Based on regression, the Missouri–Ohio relation underpredicts OC burial in Iowa reservoirs by a median value of 2011 g m^{-2} yr^{-1}, the approximate mean in that study, and further illustrates broad differences within the midcontinent agricultural region.

Given the negative relation between SedAR and %surface water in the Missouri dataset, it follows that burial rates were negatively related to %surface water ($r = -0.53$ for P, -0.48 for OC, and -0.40 for N, with $p < 0.02$). Small agricultural ponds bury C at high rates (Downing et al. 2008, Mendonça et al. 2017, Gilbert et al. 2021), a landscape-level signal of C sequestration that supports findings from elsewhere.

The drivers of burial of OC and N and P are similar, so it follows that the correlations between the accumulation rates of these 3 elements are strong (Fig. 5). All are driven by the overall sediment accumulation rate and the elemental composition of the sedimentary material. Because the variance in elemental concentrations is small relative to the overall sedimentation rate, the strong correlations are logically necessary.

Stoichiometric burial ratios

The stoichiometry of lake sediments can also be related to pelagic influences and quality of the habitat for benthic organisms (Sterner and Elser 2017). For example, high C:P or high C:N reflect high energy value for consumption or cycling by various organisms (excess OC). Low C:P would suggest extreme over-fertilization

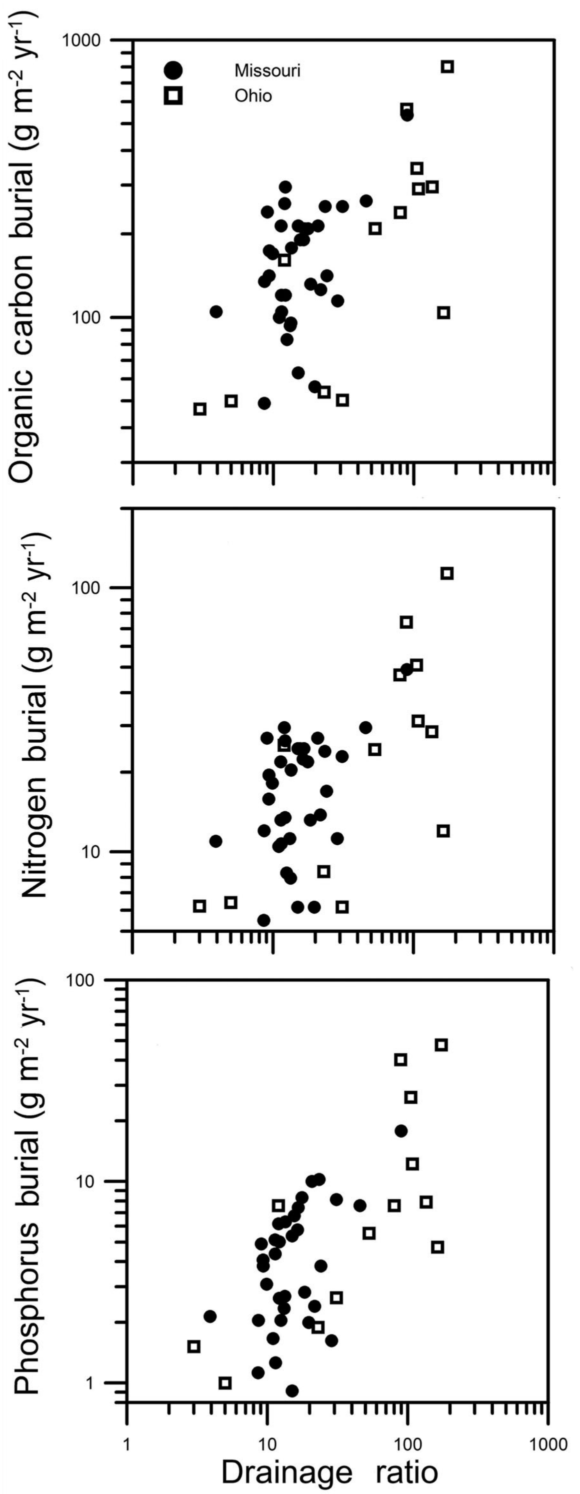

Figure 4. Relationships between the burial of OC and N and P in the sediments of Missouri and Ohio lakes related to the drainage ratio.

to the point that organisms die and sediment has excess nutrients, or that erosional loss of inorganic soils may dominate deposition, for example. High N:P suggests high P limitation and low N:P may suggests shortages of N, leading to N limitation (e.g., Cross et al. 2005).

Stoichiometric ratios in Missouri sediments were similar to those in Ohio but with larger mean values (N:P = 10 vs. 7, C:P = 114 vs. 65, and C:N = 11 vs. 9, respectively), suggesting benthic environments are more P limited in Missouri and are poorer in N and P but energy rich. In Missouri, a negative relation with WA for both N:P and C:P explained some 30% of cross-system variation ($r^2 = 0.34$ and 0.29, respectively, $n = 34$). Sediment P showed a weak positive correlation with WA ($r = 0.35$, $p = <0.05$), but elements in the numerator of these ratios were not significantly related to WA, so an increase in WA reduces the ratio. In multiple regression, %Forest aligned with increasing WA (positive coefficient) and explained variation in both elemental ratios to ∼45%. The negative correlation between %Forest and %P ($r = -0.61$, $n = 34$) accounts for the pattern; %P declines with increasing forest cover, resulting in an increase in both ratios. Taken alone, %Forest accounts for 19% of variation in N:P and 25% in C:P ($n = 34$). Forest cover is well known to impede nutrient release from watersheds (Qiu et al. 2023).

These patterns are opposite of findings in Ohio where both ratios declined with %Forest and increased with %AG (Knoll et al. 2014). Among Ohio reservoirs, both N:P and C:P showed strong positive increases with %Ag ($r^2 = 0.64$ and 0.84, respectively), but those equations underpredicted ratios in Missouri by 3 and 46, respectively. Agriculture likely supplies excess C from crop residues (Al-Kaisi and Kwaw-Mensah 2020) and excess N from high rates of fertilization with anhydrous ammonia in this region (Chatterjee 2020).

Both %OC and %N declined with suspended solids in the water column, such that NAS and WA accounted for 59% of variation in N:P and C:P ($n = 34$). For C:N, %crop and WA explained 26% of variation (partial $r^2 = 0.16$ and 0.10, respectively, $n = 34$). In Ohio, no pattern was observed between land cover and C:N, but %crop was not separated from agricultural land cover in that study (Knoll et al. 2014).

Taken together, these results suggest that larger watersheds lead to less energy-rich sediments and a greater degree of N limitation in benthic systems, reflecting the sedimentation of inorganic erosional materials in lakes with large catchments. Land use also plays a role, making benthic sediments in predominantly forested catchments richer in energy and relatively rich in P versus N. The differences between the stoichiometry of sediments in Missouri and Ohio suggest that the details of land use and regional practices can drive energy richness and nutrient limitation in the benthic system.

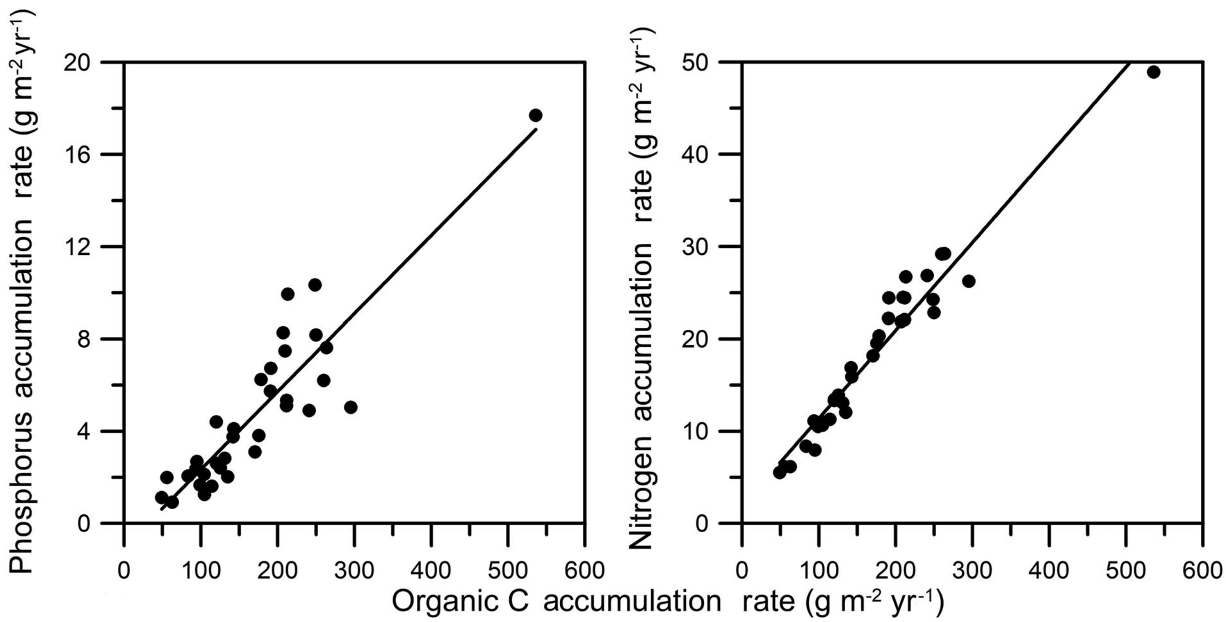

Figure 5. The correlations between P, N, and OC deposition rates in Missouri lakes.

Global patterns in OC burial rates

These regional analyses show that the nature and use of the watershed has a major effect both on the quality of sediment buried and the rate of OC sequestration afforded by diverse global lakes. In this region, because accumulation of C and major nutrients is strongly correlated, insight into the global role of lakes as sinks of important geochemical materials can be gained by examining drivers of OC accumulation. The implication from this work is that small lakes and lakes in highly disturbed watersheds are absorbing substantial sediment, C, and nutrients.

Insight into the global role of lakes as sinks for C, N, and P can be deduced from broader comparisons with C sequestration on a larger scale. Differences in OC sequestration rates in diverse lakes and impoundments, even within the same region of the United States, suggests that small variations in conditions may have profound effects. We therefore contrast our OC-deposition results with results from similar regions in the United States and with rates of OC burial across the globe. These data do not include all that have been published to date but cover much of the range of lakes and values seen globally. In a study of lakes and impoundments in one of the most disturbed agricultural regions on Earth, Downing et al. (2008) indicated that, on a global scale, the most important driver of OC burial was lake size. Within our study impoundments, however, we found little influence of lake size, perhaps because of the narrow range of sizes studied. Comparing our mid-continent data with a global collection of OC burial

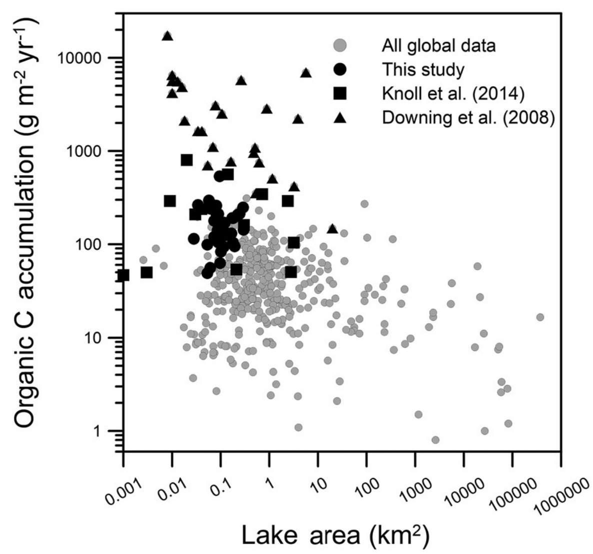

Figure 6. Global relationship between lake and pond size and OC accumulation or burial rates compared to data from this study and others in 2 similar regions (Downing et al. 2008, Knoll et al. 2014). Global data are from many sources (Mulholland and Elwood 1982, Manthorne 2002, Alin and Johnson 2007, Cordeiro et al. 2008, Landers et al. 2008, Rippey et al. 2008, Mast et al. 2010, Kunz et al. 2011, Mackay et al. 2012, Obrador and Pretus 2012, Teodoru et al. 2012, Van Metre 2012, Brothers et al. 2013, Gui et al. 2013, Heathcote et al. 2013, Hobbs et al. 2013, Anderson et al. 2014, Ferland et al. 2014, Dietz et al. 2015, Almeida et al. 2016).

data (references Fig. 6), the pattern shows our impoundments diverge from lakes studied in other regions in that they have extraordinarily high rates of OC and therefore nutrient burial. This finding suggests the

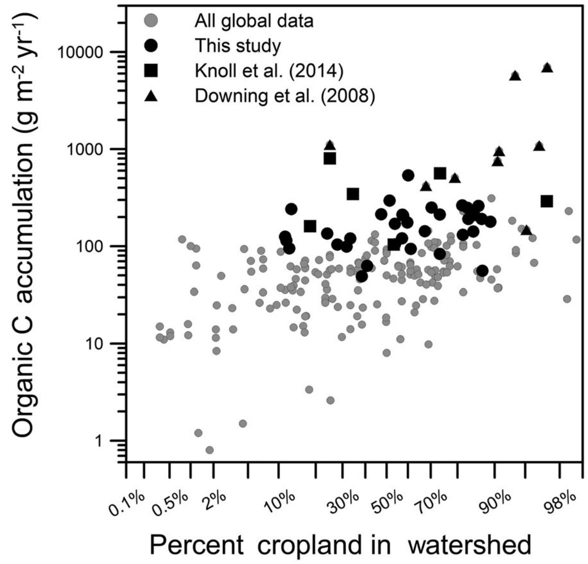

Figure 7. Global relationship between agricultural land use and OC accumulation or burial rates compared to data from this study and others in 2 similar regions (Downing et al. 2008, Knoll et al. 2014). Global data sources are as in Fig. 6.

differences are due to the intensive agricultural environment where these lakes are found, not surprising given the heavy fertilizer amendments across the region and the global effect of fertilization on sediment burial suggested by Anderson et al. (2020).

Using the global comparison data (Fig. 6), we also can array them across an axis of agricultural cropland (Fig. 7); although cropland has a positive influence on OC burial, the lakes across our region cluster together and sit distinctly above most other lakes in the global sample. This finding suggests that the format and details of agricultural land use can alter C and nutrient deposition by 1–2 orders of magnitude.

Conclusion

From this study and the work of Knoll et al. (2014), we would postulate that the drivers of these strong differences, accounting for 1–2 orders of magnitude range in OC burial, are the drainage ratio, the size of the receiving waterbody, the amount of disturbed cropland in the watershed, and the watershed soil composition. Given the unprecedented population pressure put on existing cropland (Beaulieu et al. 2019) and the high demand for impounding water for human and livestock use (Bouwman et al. 2013), we expect C and nutrient burial in impoundments to increase. As has happened in many areas of the world, land disturbance can lead to infilling, the loss of the ability of impoundments to absorb transported sediments, and the passing through of sediments to downstream systems and marine systems.

The broad conclusion of this study, and comparisons with other studies in the region and around the globe, is that the degree of C and nutrient sequestration by lakes is driven by many factors beyond simple “land use.” We postulate that the degree of land disturbance and soil loss downstream to lakes and marine systems can vary considerably with the details of soil composition, cropping systems, and landscape permeability. For example, Fraterrigo and Downing (2008) showed that, even within watersheds of uniformly high agricultural land use, downstream transport of nutrients can increase greatly with hydraulic transport capacity. Correctly understanding the global role of lakes and ponds in global biogeochemical cycles will require a more detailed comprehension of the factors driving erosional losses of C and nutrients from diverse land uses in diverse regions.

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