Organic Carbon Burial in Lakes and Reservoirs of the Conterminous United States

DATASET *in* ENVIRONMENTAL SCIENCE AND TECHNOLOGY · JUNE 2015

Impact Factor: 5.33 · DOI: 10.1021/acs.est.5b05076

7 AUTHORS, INCLUDING:

Sarah M. Stackpoole

United States Geological Survey

David Butman

University of Washington Seattle

David P Krabbenhoft

United States Geological Survey

Robert G. Striegl

United States Geological Survey

Environmental Science & Technology

Article

pubs.acs.org/est

Organic Carbon Burial in Lakes and Reservoirs of the Conterminous United States

David W. Clow,[*,†] Sarah M. Stackpoole,[‡] Kristine L. Verdin,[†] David E. Butman,[§,∥] Zhiliang Zhu,[⊥] David P. Krabbenhoft,[#] and Robert G. Striegl[§]

[†]U.S. Geological Survey, Colorado Water Science Center, Denver, Colorado 80225, United States

[‡]U.S. Geological Survey, National Research Program, Denver, Colorado 80225, United States

[§]U.S. Geological Survey, National Research Program, Boulder, Colorado 80303, United States

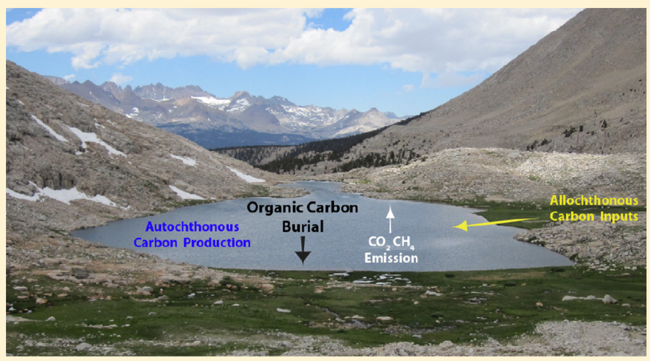
[∥]School of Environmental and Forest Sciences & Environmental Engineering, University of Washington, Seattle, Washington 98195, United States

[⊥]U.S. Geological Survey, Reston, Virginia 20192, United States

[#]U.S. Geological Survey, Wisconsin Water Science Center, Madison, Wisconsin 53562, United States

Supporting Information

ABSTRACT: Organic carbon (OC) burial in lacustrine sediments represents an important sink in the global carbon cycle; however, large-scale OC burial rates are poorly constrained, primarily because of the sparseness of available data sets. Here we present an analysis of OC burial rates in water bodies of the conterminous U.S. (CONUS) that takes advantage of recently developed national-scale data sets on reservoir sedimentation rates, sediment OC concentrations, lake OC burial rates, and water body distributions. We relate these data to basin characteristics and land use in a geostatistical analysis to develop an empirical model of OC burial in water bodies of the CONUS. Our results indicate that CONUS water bodies sequester 20.8 (95% CI: 9.4–65.8) Tg C yr^{-1}, and spatial patterns in OC burial are strongly influenced by water body type, size, and abundance; land use; and soil and vegetation characteristics in surrounding areas. Carbon burial is greatest in the central and southeastern regions of the CONUS, where cultivation and an abundance of small water bodies enhance accumulation of sediment and OC in aquatic environments.



INTRODUCTION

Inland waters are locations of intense carbon (C) cycling, processing large amounts of autochthonous and allochthonous C fixed by terrestrial and aquatic ecosystems through photosynthesis.[1−3] Lakes and reservoirs cover about 1% of the earth's surface,[4−6] but because they have high sedimentation rates and burial efficiencies, organic C (OC) burial rates in lakes and reservoirs may be 1−4 times those of the world's oceans.[1,2,7] Over the Holocene, lake sediments have stored ~420−820 Pg of OC, similar in magnitude to the amount stored in soils (~1395−1600 Pg) and terrestrial biomass (~460−560 Pg).[1,7−9] Organic C burial rates in lakes have increased substantially during the last several hundred years in response to changes in land use, intensification of agriculture, and eutrophication of surface waters.[3,10−12] Although man-made impoundments (reservoirs) store OC for shorter time periods than lakes, they often have higher OC burial rates, and the advent of large-scale construction of reservoirs during the 20th century represents an important modification to the global C cycle.[3] Quantifying OC storage in lake and reservoir sediments is essential for understanding how C moves among and is stored within terrestrial, aquatic, and atmospheric compartments of the globe.

Organic C burial in lakes and reservoirs occurs primarily through sedimentation of autochthonous organic matter generated internally through in situ primary production, and of allochthonous organic matter that is fixed on land and transported from terrestrial to aquatic systems through wind and water erosion and groundwater flow. Autochthonous production rates tend to be high in eutrophic lakes and reservoirs, where nutrients promote growth of algae and macrophytes.[13] Allochthonous inputs of organic matter often are high in disturbed areas, where erosion enhances transport of terrestrial OC and sediment to receiving water bodies.[3,14] Because of differences in the relative importance of autochthonous and allochthonous inputs, lakes tend to have

Received: January 21, 2015
Revised: May 26, 2015
Accepted: June 10, 2015

DOI: 10.1021/acs.est.5b00373
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

lower sedimentation rates and higher sediment OC concentrations than reservoirs.[3,15]

Whether from autochthonous or allochthonous sources, organic matter that settles to the sediment−water interface may be either mineralized to form CO_2, which can be emitted to the atmosphere, or buried by subsequent accumulation of sediments. In anoxic sediments, conversion of organic matter to CH_4 may occur, and this gas may be released to the atmosphere through diffusion or ebullition.[16] The percentage of organic matter that is buried relative to the amount deposited on the sediment surface is referred to as the burial efficiency.[17] In most lacustrine (lake and reservoir) sediments, the predominant form of C is organic; however, in areas with carbonate bedrock, dissolved inorganic carbon may precipitate to form secondary carbonate minerals, which may accumulate in sediments.[1,13]

The importance of C fluxes and storage in aquatic systems is receiving increasing attention in the scientific literature[1,2,7] and by policy makers. Recognizing the need for further research on C cycling, the U.S. Congress passed legislation in 2007 requiring assessments of C fluxes and storage in terrestrial and aquatic ecosystems of the U.S (Energy Independence and Security Act of 2007; P.L. 110−140). Recent publications for the conterminous U.S. (CONUS) have addressed transport of dissolved C within major river systems[18] and to the coast,[19] and gaseous emissions of CO_2 from rivers and streams[20] and from lakes.[21]

Despite the recent progress on lateral transport and CO_2 emissions from inland waters, OC burial in lakes and reservoirs of the CONUS remains poorly quantified. There have been no published national-scale assessments of OC burial in lakes of the U.S., and assessments for reservoirs have been based on sparse data sets from disparate sources. In a 1982 study, OC burial in U.S. reservoirs was estimated at 18−24 Tg C yr^{-1};[3] however, the study required approximations for key parameters, such as sediment OC concentrations and dry bulk density, because of limited data availability. A more recent study using a sediment budget approach suggested that OC burial in reservoirs may be 24 ± 7 Tg C yr^{-1}, but again sediment OC concentrations were approximated, and as the authors noted, estimates of water and soil erosion rates were highly uncertain, particularly in the western U.S.[22] Because the previous estimates were based on sparse data sets, neither was able to characterize spatial variability across the landscape, or perform a robust uncertainty analysis.

The goal of the current study is to provide the most comprehensive analysis to date on OC burial in lakes and reservoirs of the CONUS. We use nationally consistent data sets on hydrography, hypsography, climate, soils, vegetation, and land use in a geographic information system (GIS) framework to develop geostatistical models for estimating major components of the OC burial equation (see Materials and Methods, eq 1). By using a geostatistical approach, we were able to (1) examine how OC burial rates vary spatially across the CONUS in response to geomorphic, climatic, and land-use/land-cover variables, and (2) quantify uncertainties based on the standard error of regression model parameters. Our analysis benefited strongly from use of a new lacustrine sediment OC data set developed as part of this study, and of several other recently developed national data sets, including the high-resolution National Hydrography Data set (NHD), the national Reservoir Sedimentation database (RESSED), the National Inventory of Dams (NID) database, and a compilation of lake OC burial rates from previous studies in the CONUS.

MATERIALS AND METHODS

We used the following equation to calculate OC burial in lakes and reservoirs of the CONUS, based on previous studies that showed that OC burial is a function of water body area, sedimentation rates, sediment OC concentrations, and OC burial efficiency:[3,13]

$$\begin{aligned} OC_{burial}(\mathrm{Tg\,C\,yr^{-1}}) = {} & [WB_{area}(\mathrm{m^2}) \times SedRt(\mathrm{g\,m^{-2}yr^{-1}}) \\ & \times OC_{conc}(\%)/100 \times BE(\%)/100] \\ & \times 10^{-12} \end{aligned} \tag{1}$$

where OC_{burial} is the OC burial rate, WB_{area} is water body area, SedRt is sedimentation rate, OC_{conc} is OC concentration in sediments (percent by dry weight), BE is burial efficiency, and 10^{-12} is a conversion factor from grams to teragrams.

Water Body Areas. Water body areas were derived from the USGS high-resolution (1:24 000) NHD, which is a digital representation of surface water in the U.S.[23] Water bodies were classified as reservoirs if they met any of the following criteria: (1) the water body was tagged as a reservoir in the NHD, (2) the water body name in the NHD included "reservoir", or (3) the water body was included in the NID database, which includes information on 87 000 medium to large dams in the U.S.[24] Water bodies that were not classified as reservoirs were classified as lakes or ponds (lakes/ponds). The Laurentian Great Lakes were excluded from our analysis because input data on OC burial rates in the Great Lakes are sparse and their physical characteristics (primarily size) are anomalous relative to other water bodies in the CONUS; however, literature estimates of OC burial in the Great Lakes are presented for discussion.

Sediment Organic Carbon Concentrations. We measured total C (TC) concentrations in the top 1 cm of sediment from cores collected at 697 water bodies (lakes and reservoirs) during the U.S. EPA's 2007 National Lake Assessment (NLA)[25] (see Supporting Information (SI), for details on site selection, sample collection, and analyses). We assumed that TC was predominantly in OC form, based on previous studies indicating that >95% of C in lake sediments in noncarbonate terrain is organic.[26,27]

Organic Carbon Burial in Reservoirs. Reservoir sedimentation rates were calculated using data in the RESSED database, which contains information on changes in water storage capacity for 1823 reservoirs in the CONUS, as measured through repeat bathymetric surveys.[28,29] Storage capacity generally declines with time as inflowing sediments are deposited in reservoirs. We used the data on changes in storage capacity to calculate volumetric sedimentation rates (m^3 yr^{-1}) for each reservoir; these rates were converted to linear sedimentation rates (mm yr^{-1}) by normalizing to reservoir surface area, and to mass sedimentation rates (g m^{-2} yr^{-1}) by normalizing to reservoir surface area and multiplying by sediment dry bulk density (see SI for details).

Volumetric sedimentation rates for RESSED reservoirs were regressed against local landscape characteristics, including mean slope, climate, soils, vegetation, and land use, using stepwise multiple linear regression (MLR) to develop a predictive equation that was applied to all reservoirs in the CONUS; see SI for details on the MLR procedure and a complete list of potential explanatory variables (SI Table S1).

To estimate sediment OC concentrations in reservoirs across the CONUS, a generalized linear model (GLM) was developed using the same methods and potential explanatory variables as

DOI: 10.1021/acs.est.5b00373
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

in the reservoir sedimentation rate analysis, except that water body type (reservoir or lake/pond) was added as a categorical variable. Predicted reservoir sediment OC values were adjusted for burial efficiency, which was calculated based on the relation between burial efficiency and sedimentation rates established by Sobek et al.[17] (see SI and Figure S1).

Organic Carbon Burial in Lakes/Ponds. Data on modern (last ~10 years of deposition) OC burial in lakes/ponds in the CONUS were compiled from published studies that used ^{210}Pb-dated sediment cores with appropriate corrections for sediment focusing (see SI).[27,30−33] Sedimentation rates and OC concentrations in the sediment cores were measured in each of the studies. The compiled data set included sites from across the CONUS, and covered a range of land-use and trophic conditions, including relatively undisturbed lakes in the western U.S.,[26,27,32] and the northern parts of Minnesota, Wisconsin, and Michigan;[31] agriculturally impacted lakes in southern Minnesota[31] and Iowa;[30] and lakes near major urban areas.[33] To account for OC mineralization in the uppermost layers of sediment, we evaluated trends in OC with depth in cores from three of the studies.[26,27,32,33] Previous studies indicate that most mineralization occurs within the first five years after deposition,[10,34] and our results indicate an average OC loss of ~10% during that time, consistent with results from a recent study of Minnesota lakes.[10] A 10% loss would cause OC burial rates to be overestimated by ~6%; thus, we adjusted OC burial rates downward by 6% to account for mineralization. The adjusted OC burial rates were regressed against landscape characteristics, as in the reservoir sedimentation rate analysis, to build a predictive equation that was applied to all lakes/ponds in the CONUS.

Uncertainty. To estimate uncertainty, we used a Monte Carlo approach in which parameter coefficients in each of the regression models were allowed to vary randomly within their 95% confidence intervals (CIs) during each evaluation of the predictive equations. This procedure was repeated for 1000 iterations, yielding 1000 predictions for OC burial rate for each water body in the CONUS. Results were aggregated by large-scale hydrologic regions of the CONUS (2-digit HUCs; SI Figure S2), and are summarized as estimates of the median with 95% CIs.

RESULTS AND DISCUSSION

Water Body Areas. Water body type, size, and abundance have an important influence on OC burial in lakes and reservoirs. There are approximately 3.5 million water bodies larger than 0.001 km^2 in the CONUS;[5] of these, we identified 227 119 reservoirs and the rest were classified as lakes/ponds. A comparison with ground-based observations on 697 water bodies that were visited during the U.S. EPA's 2007 National Lake Assessment (NLA) indicated that our classification scheme was correct 80% of the time. Medium and large water bodies generally were correctly classified, and most of the errors were associated with small water bodies. The small water bodies include farm ponds and natural lakes that are not differentiated in the NHD, which groups them together as lakes/ponds because of the difficulty of distinguishing them using available map data.[5] Although it would be preferable not to group lakes and farm ponds for our analysis because of potential differences in OC burial rates, there currently are no high-resolution maps for the CONUS that distinguish between these two features.

Our analysis indicated that reservoirs cover 43 900 km^2, and lakes/ponds cover another 82 893 km^2, yielding a total water body area of 126 793 km^2 for the CONUS, excluding the Laurentian Great Lakes. A previous estimate for reservoirs greater than 2 km^2 in area indicated that they cover approximately 40 000 km^2 in the U.S.[35] Our estimate for total water body area is similar to the 131 000 km^2 recently estimated for water bodies in the CONUS,[5] and accounts for approximately 1.6% of CONUS area.

Water body surface area is greatest in the central and southeastern parts of the U.S., and least in the desert southwest (Figure 1). The high surface area of water bodies in the central

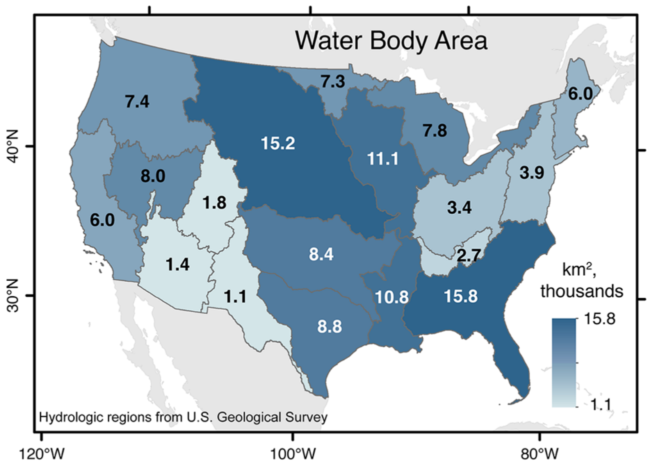


Figure 1. Surface area of water bodies in the conterminous U.S. summarized by hydrologic region.

and southeastern U.S. primarily reflects an abundance of farm ponds and reservoirs, as natural lakes are relatively uncommon in most of this area.[5,14,36,37] Although it is clear that farm ponds are quite numerous in the CONUS, their exact number, cumulative area, and specific locations are uncertain because of the mapping issues previously mentioned. One study suggests there may be ~2.6 million farm ponds in the U.S., with a surface area of approximately 21 000 km^2;[36] however, further analysis is needed to better establish their spatial attributes (abundance, size, and location).

Sediment Organic Carbon Concentrations. Measured sediment OC concentrations showed strong spatial variability (Figure 2A), and results from our GLM analysis indicate that spatial patterns in lacustrine sediment OC are influenced by water body type, soil characteristics, vegetation, and land use (Figure 2B). Median OC concentrations in lacustrine sediments sampled during the NLA were significantly higher in lakes/ponds (11.3%) than in reservoirs (4.1%; $p < 0.001$; Wilcoxon signed-rank test), and water body type was a significant explanatory variable in the GLM (Figure 2B). The regression analysis indicated that soil organic carbon (SOC) and wetlands have a positive influence on lacustrine sediment OC, while barren terrain, mean *k*-factor (a soil erodibility index;[38] see SI), and water body area have a negative influence (Figure 2B). Spatial variations in sediment OC concentrations reflect variations in the driving variables. For example, relatively high OC concentrations in lacustrine sediments in the eastern U.S., Gulf coast, and upper Midwest (Figure 2A and SI Figure S3) are attributable to high SOC and the prevalence of wetlands in those areas (SI Figure S2, Table S2). Low sediment OC concentrations in the southwestern U.S. reflect low SOC

DOI: 10.1021/acs.est.5b00373
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

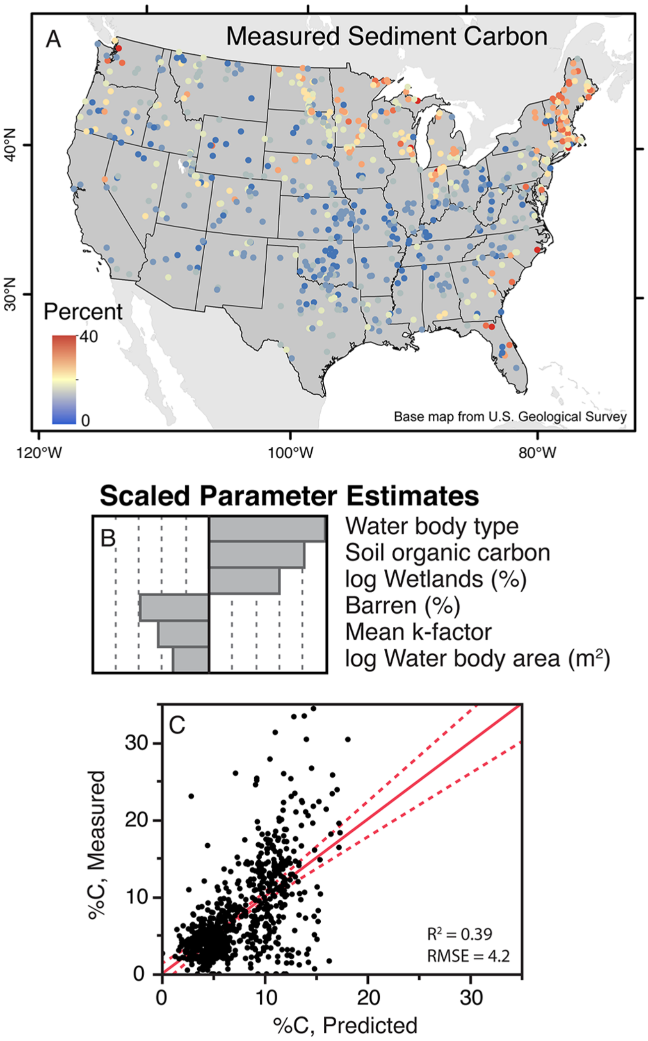


Figure 2. (A) Measured carbon concentrations in the top 1 cm of sediment in lakes and reservoirs sampled during 2007 National Lake Assessment. (B) Scaled parameter estimates for sediment carbon concentration model; scaled parameter estimates are beta coefficients centered by the mean, scaled by range/2, and show the relative influence of parameters in the regression equation. (C) Predicted versus measured sediment carbon concentrations. Solid line shows best fit of regression; dashed line indicates 95% confidence interval of best-fit line.

and the prevalence of reservoirs in those regions. The model explained 39% of the variance in lacustrine sediment OC and had a root-mean-square error (RMSE) of 4.2, indicating that a substantial amount of the variance in measured OC concentrations remained unexplained (Figure 2C; see SI for details on geostatistical modeling and regression equations).

The positive influence of SOC and wetlands on sediment OC concentrations reflects their importance as sources of allochthonous OC to water bodies.[15,39] Soil OC may be transported from hillslopes to water bodies as particulate C through wind or water erosion, or as dissolved organic carbon (DOC) via surface or subsurface flow.[40,41] Wetlands can be an important source of DOC for lakes because they often are highly productive and tend to occur at the interface between terrestrial and lacustrine systems.[41,42] Much of the allochthonous DOC in lakes is mineralized in the water column, but some flocculates and settles to the sediment surface, where it may be buried (or mineralized) over time.[39,42,43]

The negative relation between barren terrain and sediment OC (Figure 2B) reflects the importance of terrestrial vegetation (or lack thereof) as a contributor to sediment OC content. Highly erodible soils (those with high k-factors) can contribute large amounts of mineral matter to sediments during intense rain events, diluting sediment OC derived from autochthonous and allochthonous sources. Water body size is another negative influence on sediment OC concentrations, reflecting an inverse relation between productivity and lake size.[41,44]

Organic Carbon Burial in Reservoirs. Reservoir sedimentation rates have a log-normal statistical distribution, with a median of 17 mm yr^{-1}, and a mean of 44 mm yr^{-1}, based on data in the RESSED database. The rates are extremely variable, but regional patterns exist, with high rates in the western U.S. and parts of the north-central U.S., and generally low rates in the eastern U.S. (Figure 3A). The high rates in the western U.S. are attributable to varying combinations of steep terrain, sparse vegetation, and easily erodible sedimentary bedrock (SI Table S2, Figure S2).[45] In the north-central U.S., high sedimentation rates reflect the prevalence of cultivated croplands, where tilling promotes erosion (SI Figure S2).[22,46] In contrast, in the northeastern U.S. deciduous forests limit erosion, and in the southeast relatively flat terrain has a similar effect, resulting in low reservoir sedimentation rates in those areas (SI Table S2, Figure S2). In addition to these regional patterns, very high sedimentation rates occur in localized areas (Figure 3A); although we could not link the anomalous rates to specific incidents, rates of this magnitude often are associated with land disturbance caused by wildfires, landslides, debris flows, or similar episodic events.[47−49]

Previous studies have noted that reservoir sedimentation rates vary with net sediment contributing area, which is the basin area above a reservoir excluding any area above upstream reservoirs.[50,51] This relation reflects the importance of erosion and transport of allochthonous material from terrestrial landscapes to reservoirs, and is corroborated by a strong positive correlation between net contributing area and sedimentation rates in RESSED reservoirs (R^2 = 0.64; p < 0.001). Although net contributing area data are not available for most reservoirs in the U.S., reservoir surface area data are (through the NHD), and the correlation with sedimentation rate is almost as strong (R^2 = 0.56; p < 0.001). Thus, we used reservoir surface area as a surrogate for net contributing area in our MLR analysis.

In the MLR model for reservoir sedimentation rates, reservoir surface area was the strongest predictor, with a strong, positive effect (Figure 3B). Other, less important predictors in the model included mean basin slope (positive effect) and percent of basin covered by forest (negative) and cultivated crops (positive). The model explained 86% of the variance in observed volumetric reservoir sedimentation rates for reservoirs in the RESSED, and had a RMSE of 0.51 (Figure 3C; see SI). These results indicate that reservoir area (and by implication, net contributing area) is the dominant control on spatial variability in annual sediment deposition in reservoirs, while basin characteristics and land use exert a significant, but smaller influence.

Modeled reservoir sedimentation rates were lowest in the hydrologic regions of the eastern U.S. (∼8—11 mm yr^{-1}; SI Figure S4), and greatest in the west (∼15—21 mm yr^{-1}; SI Figure S4), similar to the pattern in measured sedimentation rates in RESSED reservoirs (Figure 3A). These spatial patterns are consistent with those of a previous analysis of annual

DOI: 10.1021/acs.est.5b00373
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

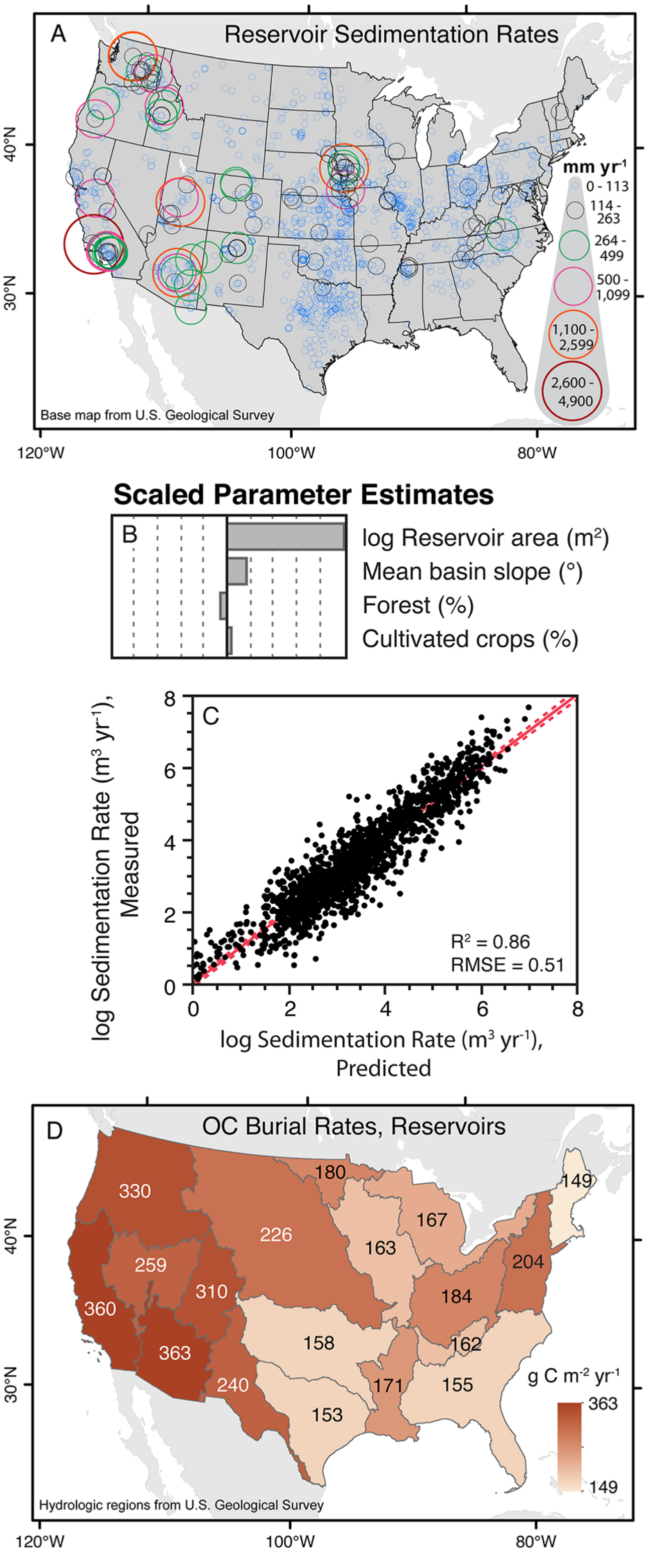


Figure 3. (A) Map showing measured linear sedimentation rates (LSRs) for RESSED reservoirs. (B) Scaled parameter estimates for reservoir sedimentation rate model. (C) Predicted versus measured volumetric sedimentation rates for reservoirs. (D) Estimated modern organic carbon (OC) burial rates in reservoirs, summarized by hydrologic regions of the conterminous U.S.

storage loss in reservoirs, which documented low rates (<0.4% yr^{-1}) in the eastern U.S., and much higher rates (>2.0% yr^{-1}) in the interior west.[45]

Organic C burial rates for reservoirs of the CONUS are estimated to range from 149 to 363 g C m^{-2} yr^{-1}, with rates in the western U.S. approximately double those in the east (Figure 3D). These rates, which are normalized to water body area, reflect the intensity of OC burial within aquatic ecosystems in a given area. The high rates in the western U.S. are mainly attributable to high reservoir sedimentation rates (SI Figure S4) rather than sediment C concentrations, which generally are low in the west (SI Figure S3A and B). Our estimates for OC burial in reservoirs are somewhat lower than those from two previous studies (350−400 g C m^{-2} yr^{-1});[3,13] however, unlike the previous studies, our estimates do not include OC burial in farm ponds, which can have very high OC burial rates[44] (farm ponds are included in our lakes/ponds category).

Organic Carbon Burial in Lakes/Ponds. Measured OC burial rates in lakes/ponds followed a log-normal distribution, with a median of 31 g C m^{-2} yr^{-1} and a mean of 46 g C m^{-2} yr^{-1}. Our MLR analysis for OC burial in lakes/ponds indicated that mean annual air temperature and k-factor have a strong positive influence, SOC and percent wetlands have a moderate positive influence, and percent forest in the basin has a moderate negative influence (Figure 4A). The model explained 74% of the variance in observed OC burial rates in lakes/ponds, and had a RMSE of 0.21 (Figure 4B).

Modeled OC burial in lakes/ponds shows a strong north−south gradient, with the highest rates in the southern part of the CONUS (Figure 4C), where mean annual air temperatures are greatest (SI Table S2). An abundance of wetlands further contributes to high OC burial rates in lakes/ponds of the lower Mississippi River valley and South Atlantic-Gulf regions, while soils with high erosivity (high k-factors) enhance OC burial in lakes/ponds in the Texas-Gulf and Arkansas-White-Red River regions (Figure 4C, SI Table S2). The regions with the lowest lakes/ponds OC burial rates are those with relatively low mean annual air temperatures, including the New England, Souris-Red-Rainy, Pacific Northwest, Upper Colorado, and Great Basin regions (Figure 4C, SI Table S2). Clearly temperature has a major influence on OC burial in lakes/ponds, probably due to the interdependence of air temperature with net ecosystem productivity, which is relatively high in the lower Mississippi and South Atlantic-Gulf regions.[52] Interestingly, a study of Swedish lakes documented a strong positive relation between temperature and OC mineralization in lake sediments, and the authors suggested warmer temperatures could lead to less OC burial in boreal lakes.[53] Additional research is needed to determine the interaction between changes in primary production and sediment OC mineralization as climate warms.

Our estimates for modern OC burial in lakes/ponds in the northern part of the CONUS (Figure 4C) are similar to contemporary OC burial rates estimated for lakes in Minnesota (25−70 g C m^{-2} yr^{-1}),[10] and for culturally impacted lakes in Europe (∼60 to ∼100 g C m^{-2} yr^{-1}).[12] The OC burial rates that we estimated for lakes/ponds in the southern CONUS are substantially higher than expected for natural lakes, but may be realistic for our combined lakes/ponds category given the importance of farm ponds and scarcity of natural lakes in the southern U.S.[14,36,37] A study of OC burial in eutrophic farm ponds in Iowa documented large and highly variable burial rates, ranging from 150 to 17 000 g C m^{-2} yr^{-1}.[44]

National-Scale Estimates of Organic Carbon Burial. Our analysis indicates that approximately 8.2 Tg C (95% CI: 6.6−10.2) is buried as OC annually in medium to large reservoirs of the CONUS. This value is lower than previous

DOI: 10.1021/acs.est.5b00373
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

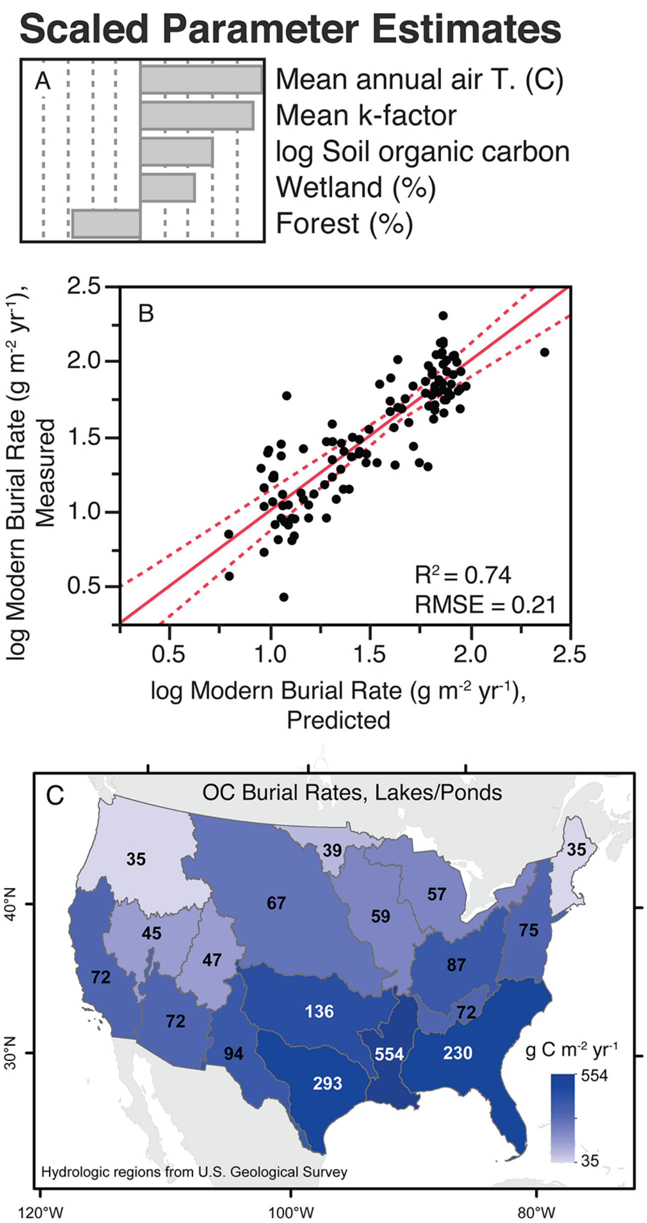


Figure 4. (A) Scaled parameter estimates for organic carbon (OC) burial rates in lakes/ponds model. (B) Predicted versus measured OC burial rates in lakes/ponds. (C) Estimated modern organic carbon (OC) burial rates in lakes/ponds, summarized by hydrologic regions of the conterminous U.S.

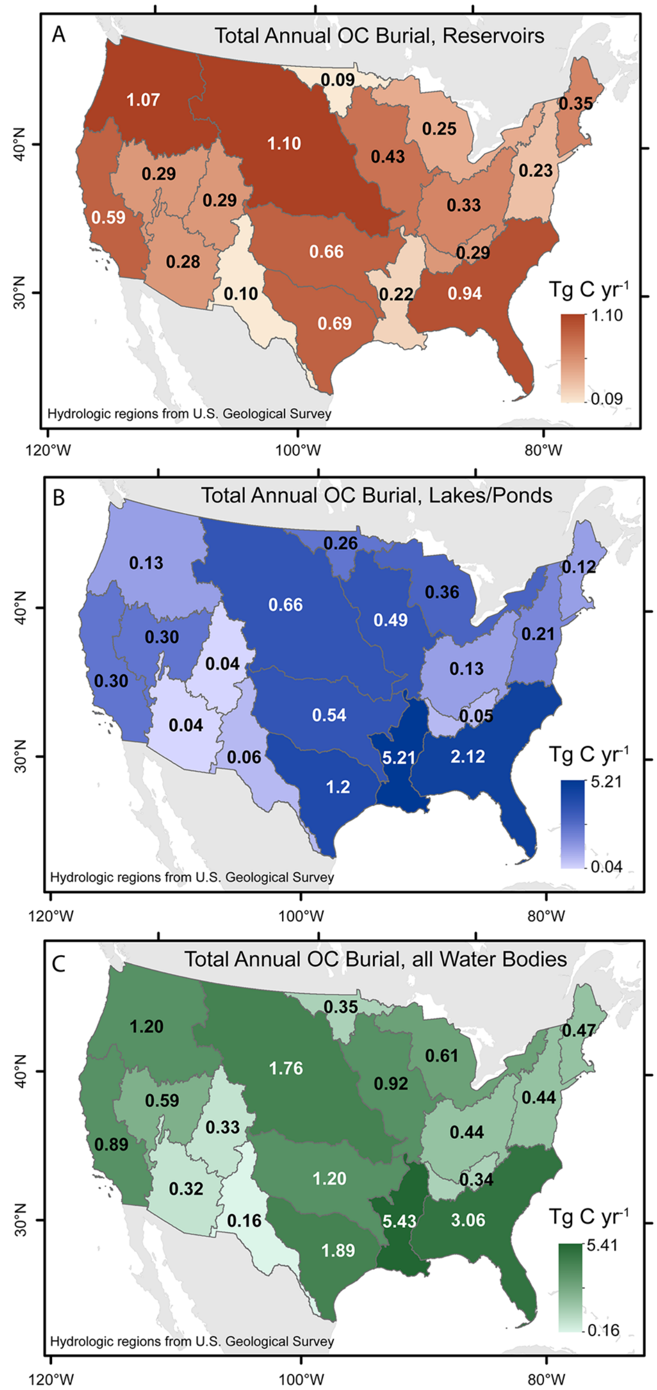


Figure 5. Estimated total annual organic carbon (OC) burial rates in hydrologic regions of the conterminous U.S. for (A) reservoirs, (B) lakes/ponds, and (C) all water bodies combined. These rates represent total annual sequestration of OC in water bodies within each region.

estimates for U.S. reservoirs,[3,13] partly because reservoir sedimentation rates may have been overestimated in previous studies (see SI), but also because we do not include most farm ponds in our reservoir category (they are included in our lakes/ponds category instead). Total annual OC burial in reservoirs is greatest in the Missouri and Pacific Northwest regions (Figure 5A), which have moderate to high OC burial rates (Figure 3D), and four of the six largest reservoirs in the CONUS.

We estimate that approximately 12.6 Tg C (95% CI: 2.8–55.6) is buried as OC annually in lakes/ponds of the CONUS. Organic C burial in lakes/ponds is greatest in the lower Mississippi, South Atlantic-Gulf, and Texas-Gulf regions (Figure 5B), accounting for over half of the CONUS total, due to the intensity of OC burial (Figure 4C) and an abundance of farm ponds, which contribute substantial water surface area in this area (Figure 1).[36]

Total annual OC burial in the CONUS is approximately 20.8 Tg C yr^{-1} (95% CI: 9.4–65.8), and spatial patterns (Figure 5C) reflect variations in water body type, size, and abundance; land use; and soil and vegetation characteristics in surrounding areas (Figure 1 and SI Figure S2, Table S2). Annual OC burial is greatest in areas that are relatively warm, intensively used for agriculture, and have large total water body surface areas, which primarily occur in the southeast and central sections of the

DOI: 10.1021/acs.est.5b00373
Environ. Sci. Technol. XXXX, XXX, XXX–XXX

CONUS. In contrast, annual OC burial is much less important in the Rio Grande, upper and lower Colorado, and Tennessee regions (Figure 5C), which have low water body surface areas and low SOC concentrations (Figure 1, SI Table S2).

In addition to burying OC, lakes and reservoirs emit C, primarily as CO_2, but also as CH_4. Emissions of CO_2 from water bodies of the CONUS have been estimated to account for 14.7 Tg C yr^{-1},[21] which is 72% of our estimate for total annual OC burial. Spatial patterns in lacustrine CO_2 emissions were similar to those of OC burial, with high emissions in the southeast and central regions of the CONUS due to high pCO_2 concentrations, and because of the high water body surface area in those regions.[21] The emissions/burial ratio found in this study (0.72) is lower than those reported for boreal and arctic/subarctic lakes in Scandinavia (4–86, mean of 30),[54] which have much lower OC burial rates due to low particulate OC inputs from surrounding land.[42,54–56] The low emissions/burial ratio in CONUS water bodies may have important implications for global C budget analyses, because it indicates that temperate water bodies are relatively effective at sequestering carbon.

Uncertainties and Gaps. There are several important sources of uncertainty in our OC burial calculations. Publication of the NHD in the late 2000s provided the first nationally consistent data set showing the distribution and area of water bodies in the CONUS. However, the NHD does not distinguish between farm ponds and small lakes, so we were unable to quantitatively estimate OC burial in the two systems separately. Although surface area estimates have been made for farm ponds in the CONUS, OC burial measurements for them are scarce outside of Iowa. Accurate assessment of the impact of farm ponds on OC burial requires additional OC burial measurements at a representative suite of sites across the CONUS, and development of cartographic methods for distinguishing farm ponds from natural lakes.

Another issue pertains to the uncertainty associated with using regression models to extrapolate from available data sets to the much larger population of water bodies in the CONUS. Development of the RESSED and sediment OC databases required major resource investments, yet both databases represent less than 1% of reservoirs in the CONUS. The number of lakes used to develop the OC burial model is similarly small, and potential error in predictions increase at both low and high OC burial rates (Figure 4B). Uncertainty is inversely proportional to the number of observations used to develop regression models,[57] so additional measurements of reservoir sedimentation rates, sediment OC concentrations, and OC burial rates in lakes and farm ponds could narrow the 95% CI of our estimates of OC burial in the CONUS.

The Laurentian Great Lakes were not included in our analysis because available data on OC burial rates are sparse, and because they are anomalously large compared to most water bodies in the CONUS. However, because they account for approximately as much water body surface area as the rest of the CONUS combined, even a rough estimate of OC burial in them is of interest. Previous studies have indicated that large lakes typically have relatively low OC burial rates; a synthesis of data for large lakes around the globe indicates that their OC burial rates typically range from 1—20 g C m^{-2} yr^{-1}, with higher rates in lakes affected by eutrophication.[58] The same study estimated that OC burial rates in Lakes Michigan, Huron, and Superior are 1–4 g C m^{-2} yr^{-1}, while rates in eutrophic Lake Erie and Lake Ontario may be 11—58 g C m^{-2} yr^{-1}; thus, total annual OC burial in the Great Lakes probably is on the order of 1—2 Tg C yr^{-1}.[58]

Human Effects. How have OC burial rates in water bodies been affected by human activities, and how might they change in the future? Several studies have linked development, land clearing, and the intensification of agriculture to increased soil erosion and transport of sediment, OC, and nutrients to receiving water bodies.[10–12] As a result of these activities, OC burial rates in lakes have increased two to five times over the past 150 years, reflecting stimulation of autochthonous production by eutrophication and enhanced allochthonous inputs related to erosion and sedimentation.[10–12,58] Large-scale construction of farm ponds and reservoirs represents another important change affecting the C cycle. Impounded area in the CONUS increased by about 4% annually from 1700 through 1960, and by about 1% per year since then; similar increases are likely in developing countries where agricultural intensification is continuing.[6] These changes in cultural practices have caused substantial alterations to the global carbon cycle, with erosion, sedimentation, and intensification of agriculture contributing to a stronger aquatic carbon sink, while nutrient loading and eutrophication enhance C emissions from aquatic ecosystems. Climate change may alter primary production (and possibly enhance C inputs to lakes), but it also may cause an increase in OC mineralization rates. A better understanding of interactions between these competing forces, and of linkages between terrestrial and aquatic C cycles, is essential for improving global C cycle models that are used to project C budgets into the future.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Details on methods related to sediment OC concentrations, reservoir sedimentation rates, burial efficiency, lake OC burial rates, geostatistical modeling, geographic information system analyses, statistical summaries, and k-factor. Tables listing potential explanatory variables (Table S1), land cover, hypsometric, and climate characteristics in hydrologic regions of the conterminous U.S. (Table S2). Figures showing burial efficiency versus log sedimentation rate (Figure S1), hydrologic regions and National Land Cover Data set (NLCD) land cover (Figure S2), estimated sediment C concentrations (Figure S3), estimated linear sedimentation rates in reservoirs (Figure S4). The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b00373.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: 303-236-6881; fax: 303-236-4912; e-mail: dwclow@usgs.gov.

Notes

The authors declare no competing financial interest

■ ACKNOWLEDGMENTS

This research was supported by the USGS LandCarbon Ecosystem Carbon Sequestration Project. We thank Alisa Mast and four anonymous reviewers for helpful comments on the manuscript, Sebastian Sobek for providing data on burial efficiency and sedimentation rates, and Peter Van Metre and Alisa Mast for providing data on OC burial rates in lakes. Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES

(1) Cole, J. J.; Prairie, Y. T.; Caraco, N. F.; McDowell, W. H.; Tranvik, L. J.; Striegl, R.; Duarte, C. M.; Kortelainen, P.; Downing, J. A.; Middelburg, J. J.; Melack, J. M. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems* **2007**, *10*, 171−184 DOI: 10.1007/s10021-006-9013-8.

(2) Tranvik, L. J.; Downing, J. A.; Cotner, J. B.; Loiselle, S. A.; Striegl, R. G.; Ballatore, T. J.; Dillon, P. J.; Finlay, K.; Fortino, K.; Knoll, L. B.; Kortelainen, P. L.; Kuster, T.; Larsen, S.; Laurion, I.; Leech, D. M.; McCallister, S. L.; McKnight, D. M.; Melack, J. M.; Overholt, E.; Porter, J. A.; Prairie, Y.; Renwick, J. A.; Roland, F.; Sherman, B. S.; Schindler, D. W.; Sobek, S.; Tremblay, A.; Vanni, M. J.; Verschoor, A. M.; Wachenfeldt, E. v.; Weyhenmeyer, G. A. Lakes and reservoirs as regulators of carbon cycling and climate. *Limnol. Ocean.* **2009**, *54* (6, part 2), 2298−2314.

(3) Mulholland, P. J.; Elwood, J. W. The role of lake and reservoir sediments as sinks in the perturbed global carbon cycle. *Tellus* **1982**, *34*, 490−499.

(4) Verpoorter, C.; Kutser, T.; Seekell, D. A.; Tranvik, L. J. A global inventory of lakes based on high-resolution satellite imagery. *Geophys. Res. Lett.* **2014**, *41* (18), 2014GL060641 DOI: 10.1002/2014GL060641.

(5) McDonald, C. P.; Rover, J. R.; Stets, E. G.; Striegl, R. G. The regional abundance and size distribution of lakes and reservoirs in the United States and implications for estimates of global lake extent. *Limnol. Ocean.* **2012**, *57* (2), 597−606 DOI: 10.4319/lo.2012.57.2.0597.

(6) Downing, J. A.; Prairie, Y. T.; Cole, J. J.; Duarte, C. M.; Tranvik, L. J.; Striegl, R. G.; McDowell, W. H.; Kortelainen, P.; Caraco, N. F.; Melack, J. M.; Middleburg, J. J. The global abundance and size distribution of lakes, ponds, and impoundments. *Limnol. Ocean.* **2006**, *51* (5), 2388−2397.

(7) Einsele, G.; Yan, J.; Hinderer, M. Atmospheric carbon burial in modern lake basins and its significance for the global carbon budget. *Global Planet. Change* **2001**, *30*, 167−196.

(8) Post, W. M.; Emanuel, W. R.; Zinke, P. J.; Stangenberger, A. G. Soil carbon pools and world life zones. *Nature* **1982**, *298*, 156−159.

(9) Sundquist, E. T. The global carbon dioxide budget. *Science* **1993**, *259*, 934−941.

(10) Anderson, N. J.; Dietz, R. D.; Engstrom, D. R., Land-use change, not climate, controls organic carbon burial in lakes. *Proc. R. Soc. London, B* **2013**, *280* (1769). DOI: 10.1098/rspb.2013.1278.

(11) Webb, R. S.; Webb, T., III Rates of accumulation in pollen cores from small lakes and mires of eastern Northe America. *Quat. Res.* **1988**, *30*, 284−297.

(12) Anderson, N. J.; Bennion, H.; Lotter, A. F. Lake eutrophication and its implications for organic carbon sequestration in Europe. *Global Change Biol.* **2014**, *20* (9), 2741−2751 DOI: 10.1111/gcb.12584.

(13) Dean, W. E.; Gorham, E. Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. *Geology* **1998**, *26*, 535−538.

(14) Renwick, W. H.; Smith, S. V.; Bartley, J. D.; Buddemeier, R. W. The role of impoundments in the sediment budget of the conterminous United States. *Geomorphology* **2005**, *71*, 99−111.

(15) Stallard, R. F. Terrestrial sedimentation and the C cycle: Coupling weathering and erosion to carbon storage. *Global Biogeochem. Cycles* **1998**, *12*, 231−237.

(16) Jacinthe, P. A.; Filippelli, G. M.; Tedesco, L. P.; Raftis, R. Carbon storage and greenhouse gases emission from a fluvial reservoir in an agricultural landscape. *Catena* **2011**, DOI: 10.1016/j.catena.2011.03.012.

(17) Sobek, S.; Durisch-Kaiser, E.; Zurbrugg, R.; Wongfun, N.; Wessels, M.; Pasche, N.; Wehrli, B. Organic carbon burial efficiency in lake sediments controlled by oxygen exposure time and sediment source. *Limnol. Ocean.* **2009**, *54* (6), 2243−2254.

(18) Stackpoole, S. M.; Stets, E. G.; Striegl, R. G. The impact of climate and reservoirs on longitudinal riverine carbon fluxes from two major watersheds in the Central and Intermontane West. *J. Geophys. Res.: Biogeosci.* **2014**, *119* (5), 2013JG002496 DOI: 10.1002/2013JG002496.

(19) Stets, E. G.; Striegl, R. G. Carbon exports by rivers draining the conterminous United States. *Inland Waters* **2012**, *2*, 177−184.

(20) Butman, D.; Raymond, P. A. Significant efflux of carbon dioxide from streams and rivers in the United States. *Nature Geosci.* **2011**, DOI: 10.1038/NGEO1294.

(21) McDonald, C. P.; Stets, E. G.; Striegl, R. G.; Butman, D. Inorganic carbon loading as a primary driver of dissolved carbon dioxide concentrations in the lakes and reservoirs of the contiguous United States. *Global Biogeochem. Cycles* **2013**, *27* (2), 285−295 DOI: 10.1002/gbc.20032.

(22) Smith, S. V.; Renwick, W. H.; Buddenmeier, R. W.; Crossland, C. J. Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States. *Global Biogeochem. Cycles* **2001**, *15*, 697−707.

(23) Simley, J. D.; Carswell, W. J., Jr. *The National Map—Hydrography*, Fact Sheet 2009-3054; U.S. Geological Survey, 2009.

(24) U.S. Army Corps of Engineers, National Inventory of Dams. http://www.agc.army.mil/Media/FactSheets/FactSheetArticleView/tabid/11913/Article/480923/national-inventory-of-dams.aspx (accessed October 29, 2014).

(25) U.S. Environmental Protection Agency *National Lakes Assessment: A collaborative survey of the Nation's lakes*, EPA 841-R-09-001; U.S. Environmental Protection Agency: Research Triangle Park, NC, 2009.

(26) Landers, D. H.; Simonich, S. L.; Jaffe, D. A.; Geiser, L. H.; Campbell, D. H.; Schwindt, A. R.; Schreck, C. B.; Kent, M. L.; Hafner, W. D.; Taylor, H. E.; Hageman, K. J.; Usenko, S.; Ackerman, L. K.; Schrlau, J. E.; Rose, N. L.; Blett, T. F.; Erway, M. M. *The Fate, Transport, And Ecological Impacts of Airborne Contaminants in Western National Parks (USA)*; United States Environmental Protection Agency, Office of Research and Development, NHEERL, Western Ecology Division: Corvallis, OR, 2008; http://www.nature.nps.gov/air/Stuides/air_toxics/wacap.cfm (accessed April 18, 2015).

(27) Landers, D. H.; Simonich, S. M.; Jaffe, D.; Geiser, L.; Campbell, D. H.; Schwindt, A.; Schreck, C.; Kent, M.; Hafner, W.; Taylor, H. E.; Hageman, K.; Usenko, S.; Ackerman, L.; Schrlau, J.; Rose, N.; Blett, T.; Erway, M. M. The Western Airborne Contaminant Assessment Project (WACAP): An Interdisciplinary Evaluation of the Impacts of Airborne Contaminants in Western U.S. National Parks. *Environ. Sci. Technol.* **2010**, *44* (3), 855−859 DOI: 10.1021/es901866e.

(28) Gray, J. B.; Bernard, J. M.; Schwarz, G. E.; Stewart, D. W.; Ray, K. T. Online interactive U.S. reservoir sedimentation survey Database. *EOS Trans. Am. Geophys. Union* **2009**, *90* (23), 199 DOI: 10.1029/2009EO230003.

(29) Ackerman, K. V.; Mixon, D. M.; Sundquist, E. T.; Stallard, R. F.; Schwarz, G. E.; Stewart, D. W. *RESIS-II: An Updated Version of the Original Reservoir Sedimentation Survey Information System (RESIS) Database*; U.S. Geological Survey, Data Series 434, 2009. http://pubs.usgs.gov/ds/ds434 (accessed April 18, 2015).

(30) Heathcote, A.; Downing, J. Impacts of eutrophication on carbon burial in freshwater lakes in an intensively agricultural landscape. *Ecosystems* **2012**, *15* (1), 60−70 DOI: 10.1007/s10021-011-9488-9.

(31) Hobbs, W. O.; Engstrom, D. R.; Scottler, S. P.; Zimmer, K. D.; Cotner, J. B. Estimating modern carbon burial rates in lakes using a single sediment sample. *Limnol. Ocean. Methods* **2013**, *11* (6), 316−326 DOI: 10.4319/lom.2013.11.316.

(32) Mast, M. A.; Manthorne, D. J.; Roth, D. A. Historical deposition of mercury and selected trace elements to high-elevation National Parks in the Western U.S. inferred from lake-sediment cores. *Atmos. Environ.* **2010**, *44* (21), 2577−2586 DOI: 10.1016/j.atmosenv.2010.04.024.

(33) Van Metre, P. C. Increased atmospheric deposition of mercury in reference lakes near major urban areas. *Environ. Pollut.* **2012**, *162*, 209−215.

(34) Gälman, V.; Rydberg, J.; de-Luna, S. S.; Bindler, R.; Renberg, I. Carbon and nitrogen loss rates during aging of lake sediment: Changes over 27 years studied in varved lake sediment. *Limnol. Ocean.* **2008**, *53* (3), 1076−1082 DOI: 10.2307/40058220.

DOI: 10.1021/acs.est.5b00373
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

(35) Ploskey, G.; Jenkins, R. *Inventory of US Reservoirs*; US Fish and Wildlife Service, National Reservoir Research Program: Fayetteville, AR, 1980.
(36) Smith, S. V.; Renwick, W. H.; Bartley, J. D.; Buddenmeier, R. W. Distribution and significance of small, artificial water bodies across the United States landscape. *Sci. Total Environ.* **2002**, *299*, 21−36.
(37) Renwick, W. H., Lakes and Reservoirs of North America. In *Encyclopedia of Inland Waters*; Likens, G. E., Ed.; Elsevier: Oxford, 2009; Vol. *2*, pp 524−531.
(38) Goldman, S. J.; Jackson, K.; Bursztynsky, T. A. *Erosion and Sediment Control Handbook*; McGraw-Hill: New York, 1986.
(39) Molot, L. A.; Dillon, P. J. Storage of terrestrial carbon in boreal lake sediments and evasion to the atmosphere. *Global Biogeochem. Cycles* **1996**, *10* (3), 483−492 DOI: 10.1029/96GB01666.
(40) Ritchie, J. C. Carbon content of sediments of small reservoirs. *J. Am. Water Resour. Assoc.* **1989**, *25* (2), 301−308 DOI: 10.1111/j.1752-1688.1989.tb03065.x.
(41) Wetzel, R. G. *Limnology: Lake and River Ecosystems*, 3rd ed.; Academic Press, Elsevier: London, 2001; p 1006.
(42) Kortelainen, P.; Pajunen, H.; Rantakari, M.; Saarnisto, M. A large carbon pool and small sink in boreal Holocene lake sediments. *Global Change Biol.* **2004**, *10*, 1648−1653.
(43) Hanson, P. C.; Pollard, A. I.; Bade, D. L.; Predick, K.; Carpenter, S. R.; Foley, J. A. A model of carbon evasion and sedimentation in temperate lakes. *Global Change Biol.* **2004**, *10*, 1285−1298 DOI: 10.1111/j.1365-2486.2004.00805.x.
(44) Downing, J. A.; Cole, J. J.; Middleburg, J. J.; Striegl, R. G.; Duarte, C. M.; Kortelainen, P.; Prairie, Y. T.; Laube, K. A., Sediment organic carbon burial in agriculturally eutrophic impoundments over the last century. *Global Biogeochem. Cycles* **2008**, *22*. DOI: 10.1029/2006GB002854.
(45) Graf, W. L.; Wohl, E.; Sinha, T.; Sabo, J. L. Sedimentation and sustainability of western American reservoirs. *Water Resour. Res.* **2010**, *46* (12), W12535 DOI: 10.1029/2009WR008836.
(46) McIntyre, S. C. Reservoir sedimentation rates linked to long-term changes in agricultural land use. *J. Am. Water Resour. Assoc.* **1993**, *29* (3), 487−495 DOI: 10.1111/j.1752-1688.1993.tb03226.x.
(47) Reneau, S. L.; Katzman, D.; Kuyumjian, G. A.; Lavine, A.; Malmon, D. V. Sediment delivery after a wildfire. *Geology* **2007**, *35* (2), 151−154 DOI: 10.1130/g23288a.1.
(48) Moody, J. A.; Martin, D. A. Synthesis of sediment yields after wildland fire in different rainfall regimes in the western United States. *Int. J. Wildland Fire* **2009**, *18* (1), 96−115 DOI: 10.1071/WF07162.
(49) Cannon, S. H.; Reneau, S. L. Conditions for generation of fire-related debris flows, Capulin Canyon, New Mexico. *Earth Surf. Proc. Land.* **2000**, *25* (10), 1103−1121.
(50) Dendy, F. E.; Champion, W. A.; Wilson, R. B., Reservoir sedimentation surveys in the United States. In *Man-Made Lakes: Their Problems and Environmental Effects*; Ackermann, W. C., White, G. F., Worthington, E. B., Eds.; American Geophysical Union: Washington, D.C., 1973; pp 349−357.
(51) Minear, J. T.; Kondolf, G. M. Estimating reservoir sedimentation rates at large spatial and temporal scales: A case study of California. *Water Resour. Res.* **2009**, *45* (12), W12502 DOI: 10.1029/2007WR006703.
(52) McGuire, A. D.; Melillo, J.; Joyce, L.; Kicklighter, D.; Grace, A.; Moore, B.; Vorosmarty, C. Interactions between carbon and nitrogen dynamics in estimating net primary productivity for potential vegetation in North America. *Global Biogeochem. Cycles* **1992**, *6* (2), 101−124.
(53) Gudasz, C.; Bastviken, D.; Steger, K.; Premke, K.; Sobek, S.; Tranvik, L. J. Temperature-controlled organic carbon mineralization in lake sediments. *Nature* **2010**, *422*, 478−481 DOI: 10.1038/nature09186.
(54) Kortelainen, P.; Rantakari, M.; Pajunen, H.; Huttunen, J. T.; Mattsson, T.; Juutinen, S.; Larmola, T.; Alm, J.; Silvola, J.; Martikainen, P. J. Carbon evasion/accumulation ratio in boreal lakes is linked to nitrogen. *Global Biogeochem. Cycles* **2013**, *27* (2), 363−374.
(55) Kortelainen, P.; Rantakari, M.; Huttunen, J. T.; Mattsson, T.; Alm, J.; Juutinen, S.; Larmola, T.; Silvola, J.; Martikainen, P. J. Sediment respiration and lake trophic state are important predictors of large CO_2 evasion from small boreal lakes. *Glob. Change Biol.* **2006**, *12* (8), 1554−1567.
(56) Jansson, M.; Hickler, T.; Jonsson, A.; Karlsson, J. Links between terrestrial primary production and bacterial production and respiration in lakes in a climate gradient in subarctic Sweden. *Ecosystems* **2008**, *11* (3), 367−376.
(57) Helsel, D. R.; Hirsch, R. M. *Statistical Methods in Water Resources*; Elsevier: Amsterdam, The Netherlands, 1992; Vol. *49*, p 522.
(58) Alin, S. R.; Johnson, T. C. Carbon cycling in large lakes of the world: A synthesis of production, burial, and lake-atmosphere exchange estimates. *Global Biogeochem. Cycles* **2007**, *21* (3), GB3002 DOI: 10.1029/2006GB002881.

DOI: 10.1021/acs.est.5b00373
Environ. Sci. Technol. XXXX, XXX, XXX−XXX