Determination of lake sediment accumulation rates in an agricultural watershed using lead-210 and cesium-137

D.G. Wren, J.R. Rigby, G.R. Davidson, and M.A. Locke

Abstract: Quantifying the effectiveness of erosion control practices in watersheds remains a difficult problem. Determination of recent sediment accumulation rates for lake sediments in agricultural watersheds using radioisotopes, such as lead-210 (^{210}Pb) and cesium-137 (^{137}Cs), is potentially a valuable means of assessing the effectiveness of soil conservation practices at the watershed scale. The predominance of sediment arriving in runoff from the watershed, variable sedimentation rates, and mechanical mixing of soil in nearby fields all present challenges in the conversion of radioisotope data to sedimentation rates. Four sediment cores from Beasley Lake, Mississippi, were used to demonstrate the application of the Constant Initial Concentration (CIC) model for calculating sediment age from the distribution of ^{210}Pb bottom sediments. The activity of ^{137}Cs was used to supplement the ^{210}Pb data by providing a benchmark date within the core to calibrate the CIC model. Three of the four cores showed reductions in sediment accumulation rate within the 30 years prior to core collection in 2008 and 2011 by at least 50% relative to rates from before the adoption of soil conservation measures in the watershed. The most recently resolved rates were approximately 0.5 cm y^{-1} (0.2 in yr^{-1}). The study demonstrates the application of the CIC model for developing sediment accumulation chronologies in agricultural catchments.

Key words: erosion—radioisotope analysis—sediment accumulation—soil conservation

Accurate assessment of present and historic watershed-level erosion rates is necessary for the continued improvement of soil conservation practices (Foster and Walling 1994). While erosion at the watershed scale is of practical interest for management and conservation purposes, few studies have addressed erosion at this scale due to the cost and technical challenges of the measurements (Mausbach and Dedrick 2004). Erosion rates are instead most often measured at small scales, such as plot or field scale (e.g., Toy et al. 2002; Stroosnijder 2005). Scaling these plot results up to the watershed scale for management purposes is challenging due to factors such as lack of spatial coverage in plot studies, the need for data collection before adoption of soil conservation practices, and the cost of instrumentation and sample collection for plot-scale soil erosion studies.

Although methods that are used for small-scale erosion measurements are difficult to extrapolate to watershed scale, watersheds that drain into a lake can be ideal systems for measuring watershed scale erosion rates (Morris and Fan 1997). In the Mississippi River alluvial plain, oxbow lakes often receive water from watersheds in the tens to hundreds of square kilometers and only release water from a single stage-dependent outlet at the downstream end of the lake, resulting in large residence times for both water and sediment. In these watersheds, sediment capture from runoff events is nearly complete (Dendy 1974), providing a continuous record of watershed erosion with time. Additionally, the Mississippi Delta Management Systems Evaluation Area (MD-MSEA) project (Nett et al. 2004) monitored oxbow lakes and improved surrounding watersheds as part of a large study aimed at improving water quality in the largely agricultural Mississippi Delta region, providing valuable background information.

Radioisotope Dating of Sediments. The use of lead-210 (^{210}Pb) for developing chronologies of sediment accumulation from deposited lake sediments is well established. In this section, the methodology is briefly described based on reviews by Appleby and Oldfield (1978, 1992), Appleby (2001), and Sanchez-Cabeza and Ruiz-Fernandez (2012). Lead-210 is a naturally occurring radionuclide produced from radon-222 (^{222}Rn) within the uranium-238 (^{238}U) decay series in sediment. Within the soil, the ^{222}Rn and ^{210}Pb activities reach an equilibrium concentration based on their relative half-lives. Some ^{222}Rn gas, however, escapes the soil and is delivered to the atmosphere before decaying. The decay of atmospheric ^{222}Rn produces ^{210}Pb that then falls out due to precipitation or dry-fall and is readily adsorbed to surface sediment particles. These surface sediments receive ^{210}Pb from both the atmospheric and terrestrial decay of ^{222}Rn, while sediments below the shallow surficial layer only receive ^{210}Pb from the terrestrial ^{222}Rn trapped in the soil. Thus, surface soils have increased ^{210}Pb activity relative to deeper soils. These surface soils and their excess ^{210}Pb are transported to lakes by runoff and deposited on the lake bottom. The deposited ^{210}Pb decays over time, resulting in a decrease in ^{210}Pb activity with depth toward the equilibrium supported level. Slower sediment accumulation rates are reflected in the sediment column by larger changes in activity over a given depth interval. The method ceases to be informative at the depth where excess ^{210}Pb activity cannot be detected above the background activity, which corresponds to an age of around 100 years, since only approximately 4% of excess ^{210}Pb may be expected to remain after this time.

The use of cesium-137 (^{137}Cs) for radiometric dating takes advantage of radioactive fallout resulting from the peak in atmospheric nuclear bomb testing that occurred in 1963. In many sediment cores, a clear spike in ^{137}Cs can be used to identify the sediment horizon

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deposited in 1963 (Appleby 2001; Ritchie et al. 1973). A mean sediment accumulation rate since 1963 can then be inferred from the age of the dated horizon and the thickness of sediment above it.

Application of Radioisotope Dating in Agricultural Watersheds. Sediment accumulation from an agricultural watershed presents a challenging environment for the application of radioisotope dating (Dercon et al. 2012). Lead-210 can be introduced to the lake by direct washout from the atmosphere and through ^{210}Pb found both in solution and adsorbed to soil particles in runoff. In a watershed where the lake receives a substantial fraction of its runoff from cultivated fields the combination of farm practices and precipitation regime can result in large and highly variable sediment accumulation rates. Where ^{210}Pb activity in lake sediments is dominated by sediment deposited from watershed runoff, rather than direct atmospheric deposition to the lake surface, the ^{210}Pb activity profile may display a pattern inconsistent with expected exponential declines in activity with depth. The resulting ^{210}Pb activity profiles may reflect several processes, such as dilution of atmospheric fallout by higher sedimentation rates, discontinuous sediment accumulation, preferential sedimentation, and sediment mixing. The data from each sediment core should be examined in order to detect areas where these processes are indicated by ^{210}Pb activity that does not generally decrease with depth. The following paragraphs describe the two basic approaches for relating sediment age to radioisotope activity: constant initial concentration (CIC) and constant rate of supply (CRS; Appleby 2001).

In the CIC model, it is assumed that sediments have a constant initial concentration of ^{210}Pb, or equivalently, that the flux of ^{210}Pb to the lake bed is proportional to the sedimentation rate. In the CIC model, the age of a sediment layer at depth m can be calculated from the following:

$$C(m) = C(0)e^{-\lambda t}, \tag{1}$$

where C is the activity of ^{210}Pb, λ is the ^{210}Pb decay constant (0.03114 y^{-1}), and t is sediment age. Note that within any region of a core for which the CIC assumption applies, the difference in age between two points within the region can be determined from equation 1 above. In studies, such as Wren

and Davidson (2011), Wren et al. (2008), and Brugam (1978), where sedimentation rates were determined from lines fitted through sections of the ^{210}Pb profile, the CIC model is implicitly assumed. The assumption of CIC should hold for the interval over which the model is applied, especially in the case of variable sedimentation rates.

In the CRS model, it is assumed that the flux of unsupported ^{210}Pb deposition from the atmosphere to the lake bed is constant while sediment delivery may vary, resulting in varying initial concentrations of ^{210}Pb in lake sediments. It is assumed that ^{210}Pb is quickly transferred from the water column to the bed of a lake and that ^{210}Pb is not redistributed after deposition. The CRS model, unlike the CIC model, is therefore applicable where changes in sedimentation rate result in changes to initial unsupported ^{210}Pb concentrations. Dates are calculated from the distribution of ^{210}Pb inventory, rather than from the relationship between ^{210}Pb activities at two depths, as in the CIC model. CRS model dates can be found from the following:

$$A = A(0)e^{-\lambda t}, \tag{2}$$

where A is the ^{210}Pb residual activity in Bq m^{-2} for sediments at time, t. A and $A(0)$ are found through numerical integration of the distribution of ^{210}Pb concentration with depth (Appleby 2001).

For the highest confidence in sediment dating, it is necessary to have a reference date for a sediment horizon, such as that provided by the 1963 bomb-pulse derived spike in ^{137}Cs activity, to use for comparison of the dating models. Disagreement of CRS/CIC model dates with reference ages from ^{137}Cs may indicate that the supply rate of ^{210}Pb to the site is variable. Specifically, discrepancies with CIC model dates indicate variations in the initial concentration that may be caused by flood events, sediment slumps, turbidity currents, and major land-use changes (Appleby 2001; Appleby and Oldfield 1992).

Present Study. The primary goals of this study were to (1) use sediments deposited in Beasley Lake, Mississippi, to determine recent sediment accumulation rates at several locations in the lake; and (2) determine the best methods for analyzing radioisotope data from an agricultural watershed. The effects of variable sedimentation rate, caused by changes in soil erosion from the watershed,

are emphasized throughout the description of methodology and results. The approach for analyzing the ^{210}Pb data is based on the CIC method, but its application is tailored to match the characteristics of the data. The results are from three sediment cores collected in 2011 plus a core collected in 2008 as part of the work described in Wren and Davidson (2011), all from Beasley Lake, Mississippi. Sediment accumulation rates from the four cores, estimated using a combination of approaches for analyzing ^{210}Pb and ^{137}Cs data, are reported and discussed.

This study differs from the previous work of Wren and Davidson (2011), which also involved study of sediment accumulation rates in Beasley Lake, Sunflower County, Mississippi, United States, as part of a larger study of five lakes. The two studies differ in the number of cores that were collected, the spatial extent covered by the cores, and by the analysis methodology. The previous study showed decreased sediment accumulation rates that could be attributed to soil conservation practices in the watershed, but it could not answer the question of possible variability of sediment accumulation rates in different parts of the lake, and only one approach to analyzing the radioisotope data was used. Additionally, the method used to analyze the radioisotope data in the 2011 study relied on the choice of a breakpoint in the data, which was then calibrated to match a date for changes in erosion control practices in the watershed. The choice of Beasley Lake for further study was based on the finding of reduced rates from the Wren and Davidson (2011) study, making it a good test case for continued development of methodology for detecting recent changes in sediment accumulation rates from radiometric data.

Study Area. Beasley Lake is a 25 ha (61.7 ac) oxbow lake formed by the nearby Sunflower River in Sunflower County, Mississippi, United States (figure 1). The lake is in the largely agricultural Big Sunflower River watershed that is approximately 67% row crops. The main crops grown in the watershed include corn (*Zea mays* L.), soybean (*Glycine max* L.), and cotton (*Gossypium* L.) grown on a rotating basis. The Beasley Lake watershed is approximately 625 ha (1,544 ac). North to south elevation along a 1.8 km (1.1 mi) transect centered on the lake varies by approximately 2 m (6 ft). From a bathymetry study conducted in 2007, the

lake bottom smoothly slopes downward towards the middle of the lake, with a mean depth of approximately 1.8 m (5.9 ft). Based on outflow data from the lake collected from 2006 to 2014, typical residence time is on the order of 20 days, ensuring a high particle trapping efficiency. The primary inflow is from the riparian channel that can be seen in figure 1. A secondary inflow is from the sedimentation basin, also shown in figure 1. Backflow into the lake has only occurred once since monitoring at the site began in 1996. No records exist regarding backflow prior to 1996.
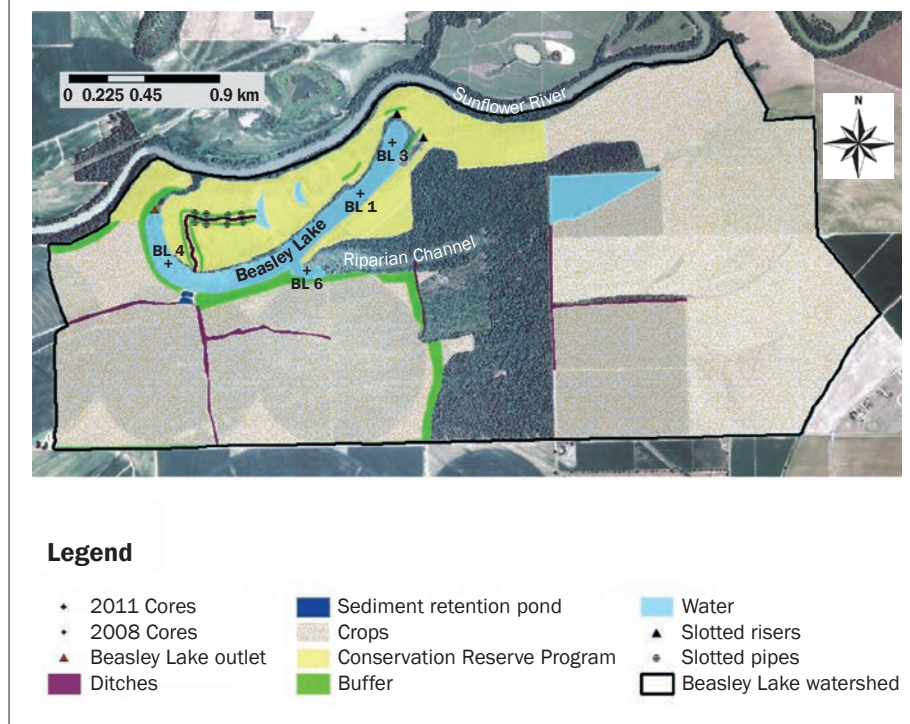
The addition of soil erosion mitigating management practices in the Beasley Lake (figure 1) watershed took place in roughly five major stages over the years 1996 to 2010 (Lizotte et al. 2014; Locke et al. 2008):

1. In 1996, about 5.4 ha (13.3 ac) of switchgrass vegetative filter strips were added at edge-of-field locations around the lake. Also, in 1996, drainage culverts were positioned at low elevations, and some used slotted board risers to slow the rate of runoff. There is no data for watershed practices prior to 1996.

2. In 2001 to 2002, conservation tillage for cotton and soybeans was implemented over an additional area of approximately 300 ha (741 ac) relative to previous years.

3. In 2003 to 2004, an area of approximately 112 ha (276.8 ac) of land north of the lake was planted in eastern cottonwood (*Populus deltoides* Bartr. Ex. Marsh.), oak (*Quercus* sp.), and hickory (*Carya* sp.) trees as part of the Conservation Reserve Program (CRP).

4. In 2006 to 2007, an additional 9 ha (22.2 ac) of land south of the lake was converted to a vegetative quail (*Colinus virginianus*) buffer.

5. In 2010, a sedimentation basin was constructed adjacent to a lake entry point at the convergence of two major drainage ditches that carry runoff from approximately 220 ha (543.6 ac) of cultivated land south and west of the lake.

Beasley Lake, Mississippi, is an ideal study site because of its high watershed to lake area ratio, minimal throughput, and high trapping efficiency, making the lake particularly sensitive to inputs from the surrounding watershed (Foster and Walling 1994; Dearing and Foster 1993). Lag time between implementation of soil conservation practices and reductions in soil erosion varies with prac-

Figure 1
Beasley Lake watershed, Mississippi, United States. Note that the Sunflower River flows east to west, the water body east of Beasley Lake is temporary storage, and the dark areas southeast of the lake are forested.

Legend

- 2011 Cores
- 2008 Cores
- Beasley Lake outlet
- Ditches
- Sediment retention pond
- Crops
- Conservation Reserve Program
- Buffer
- Water
- Slotted risers
- Slotted pipes
- Beasley Lake watershed

tice, but can be rapid for practices such as filter strips, which have been shown to be effective as little as one year after installation (Meals 1996; Meals et al. 2010). In addition, previous research in the watershed has resulted in supporting knowledge with respect to management practices, land use, and ecological activity (Locke et al. 2008; Lizotte et al. 2010).

The difficulties in interpreting sediment accumulation data and applying them over time at the watershed scale, such as the coarse time resolution of the sediment accumulation data and lack of detailed historical data for many watersheds, are discussed by Dearing et al. (1987). These difficulties do not detract from the usefulness of the method, but Dearing et al. (1987) suggest that a carefully chosen lake and surrounding watershed can increase the accuracy of historical reconstructions. This again supports the choice of Beasley Lake, Mississippi, for continued work on the connections between land use and sediment accumulation rates, especially in the unique, widely cultivated environment of the Mississippi Alluvial floodplain.

Materials and Methods

Collection and Analysis of Sediment Cores. Sediment cores were collected using a weighted, vibrating coring device to push 10.2 cm (4 in) diameter aluminum irrigation pipe into sediment deposits. The vibracoring method has been shown to extract relatively undisturbed bottom sediments due to liquefaction of the sediment at the vibrating interface between the core pipe and sediment (Lanesky et al. 1979; Smith 1984). Core pipes were cut to match the length of the core upon removal from the lake bed, capped, and stored at 4°C (40°F) until processed. The compaction ratio, assumed to be constant with depth, was determined by dividing the depth of core-pipe penetration by the length of the sediment core. It was only possible to determine rate of compaction using the vibracoring system when the head was underwater during coring; therefore, only the average rate of compaction throughout the cores could be determined. It was not possible to stop coring and take measurements of the level of the core within the pipe, since inrushing water would have destroyed the low-density top layers of material. The level of sediment in the core pipe was measured immediately after removing

the vibracoring head after raising the core. The compaction ratio likely does vary with sediment density, but this was offset by normalizing the core increment lengths by water content. Individual core increments were collected using a piston core extruder. A threaded rod pushed a piston 0.5 cm (0.2 in) per turn through a section of core pipe, enabling precise subsampling. During core extrusion and in subsequent sample preparation steps, the core increments were inspected for visible stratigraphy, such as sand lenses, and none were observed. Note that the word "sample" will be used throughout the paper to refer to values, such as ^{210}Pb activity, measured for one increment of a sediment core.

Four locations for sediment cores were chosen, and some of these were adjacent to drainage inlets associated with nearby land management practices or other watershed features. Due to the expense of radioisotope analysis, it was not possible to include replicated cores from each location; however, as reported in Wren and Davidson (2011), two cores from Wolf Lake that were separated by about 1 m (3.3 ft) yielded consistent results (see figure 7 and discussion on repeatability in Wren and Davidson [2011]). Cores that are near one another should yield similar results for sedimentation rate, and they should only differ due to procedural discrepancies. Cores at larger distances may have sedimentation rates that differ because sediment delivery to the locations is different.

The northernmost section of the lake, which is surrounded by land in the CRP and is adjacent to an inlet draining through a constructed wetland, is represented by BL3. The section of the lake that receives input directly from a riparian channel is represented by BL6. The western end of the lake, near the inlet for two major ditches that drain approximately 220 ha (543.6 ac) of cultivated land, is represented by core BL4. Since BL1 was part of a previous study aimed at characterizing the sedimentation regime with a single core, it was intentionally placed in a location that was as far as possible from direct input to the lake. The water depth in which the cores were collected was 1.2 m (3.9 ft) for BL6, 1.7 m (5.5 ft) for BL3 and BL4, and 2 m (6.5 ft) for BL1. Note that BL2, which was a wetland core collected for a related study, and BL5, which showed evidence of mechanical mixing, are not reported on here.

Lead-210 and ^{137}Cs activities were determined using a High Purity Germanium (HPGe) gamma detector from powdered, bulk sediment samples that were ground, packed, and sealed into 0.7 cm (0.3 in) diameter petri dishes and counted for 24 to 48 hours after being stored for at least 21 days (Allison et al. 2007). Cesium-137 activities were determined using the 661.6 keV photopeak (Allison et al. 2007). Total ^{210}Pb activity was determine from the 46 keV photopeak, and supported ^{210}Pb activities were determined by using averaged activities of the ^{226}Ra daughters ^{214}Pb (295 and 352 keV) and ^{214}Bi (609 keV; Allison et al. 2007). Detector efficiencies for this geometry were calculated using a natural sediment standard (International Atomic Energy Agency [IAEA]-300 Baltic Sea sediment), and detector backgrounds at each energy of interest were determined using petri blanks (Cutshall et al. 1983). Sediment accumulation rates based on ^{210}Pb assumed a constant rate of ^{210}Pb supply and rate of atmospheric ^{210}Pb fallout over the period of interest.

Samples were initially weighed wet, dried at 60°C (140°F) for 48 hours and weighed again. The mass of water in each increment was found by subtracting the mass of dry material from the mass of the wet material. The water content was found by dividing the mass of water by the wet mass of the sample. Core sample thickness and depth were normalized to mean water content (Martin and Rice 1981). This step was necessary to account for compaction in lower levels and high water content in upper levels of the cores. Recently deposited sediments with high water content will often be compressed as additional sediment accumulation decreases pore water content of the recently buried layer. In the compressed state, the thickness of the older strata may be much lower than when the sediments were originally deposited. Normalizing by water content accounts for this difference and is particularly important when attempting to make comparisons between recent and older sediment accumulation rates.

Particle sizes were measured for the top 40 cm (15.7 in) of core BL3. The samples were oven dried as described previously and then ground with a mortar and pestle. The <0.62 mm (<0.02 in) fraction was removed by wet sieving before being shaken for approximately 12 hours in a sodium hexametaphosphate ([NaPO$_3$]$_6$) solution. The

dry mass of the >0.62 mm fraction was the sand fraction, and the <0.62 mm fraction was sized using a Micromeritics Sedigraph.

Identification of Cesium-137 Peak from Limited Data. Given the limited resolution in the ^{137}Cs profiles, the choice of a depth representing the maximum activity presents the potential for significant errors in the location of the peak. There are two ways to approach this problem: (1) using the depth of the greatest measured activity, or (2) an intermediate point between the two highest measured activities. To better estimate the peak location, a continuous asymmetric function was fitted to the ^{137}Cs profiles. This bi-Gaussian function (Buys and de Clerk 1972) is the piecewise juxtaposition of two Gaussian distributions with the same mean (or peak location) but with different standard deviations and has the following form:

$$f(z) = \begin{cases} \alpha + \dfrac{\delta_1}{\sqrt{2\pi\sigma_1{}^2}} e^{\frac{-(z-\mu)^2}{2\sigma_1{}^2}} & z < \mu \\[2em] \dfrac{\delta_2}{\sqrt{2\pi\sigma_2{}^2}} e^{\frac{-(z-\mu)^2}{2\sigma_2{}^2}} & z \geq \mu \end{cases}, \quad (3)$$

where μ is the depth of the peak activity, σ_1 and σ_2 are the standard deviations of the two sides of the distribution, α is a nonzero offset to account for residual ^{137}Cs activity in recent sediments, and δ_1 and δ_2 are scaling factors, with δ_2 chosen so that the function is continuous at $z = \mu$. The result of this fitting procedure is shown in figure 2. Error bars on the ^{137}Cs peak locations in figures 3 through 6 reflect standard deviations, σ_1 and σ_2, as a measure of the uncertainty in the peak location and reflect conservative estimates of the uncertainty.

Selection of Lead-210 Dating Model. Both the CRS and CIC models make strong assumptions about the processes of ^{210}Pb deposition in lake sediments in order to derive a chronology of sediment accumulation. The CRS model, which may also be referred to as the Constant Flux Model, assumes that the flux of ^{210}Pb to the lake sediments is a constant:

$$C_i = \frac{f}{r_i}, \quad (4)$$

where C_i is the concentration of ^{210}Pb in the sediment layer (Bq kg^{-1}), f is the flux of ^{210}Pb to the sediment surface (Bq m^{-2} y^{-1}), and r_i is the mass flux rate (kg m^{-2} y^{-1}). Note that the mass flux (and thus accumulation) rate may vary within the core, but the basic assump-

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Figure 2
Cesium-137 (^{137}Cs) data and bi-Gaussian peak fits for (a) BL1, (b) BL3, (c) BL4, and (d) BL6.

Legend
• ^{137}Cs   — Fit
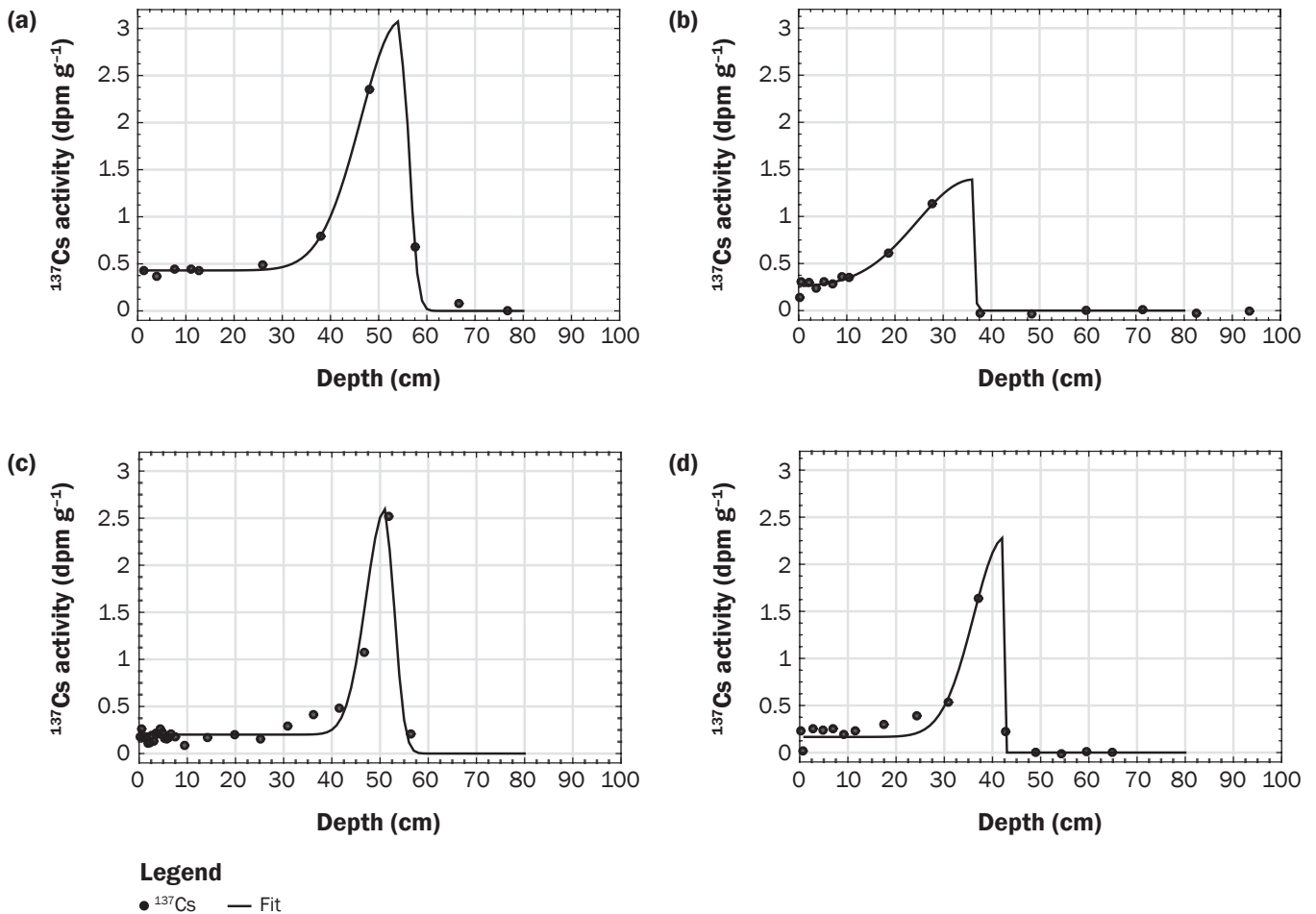
tion is that the concentration of ^{210}Pb in the sediments is inversely proportional to the accumulation rate. This assumption holds when inputs of ^{210}Pb are predominantly from direct atmospheric fallout to the lake so that changes in accumulation rate do not result in additional inputs of ^{210}Pb; therefore, the CRS model assumption is not likely valid in watersheds where there is a significant contribution of ^{210}Pb from eroded sediment mobilized from the surrounding catchment, as is often the case on working agricultural lands. Appleby (2001) states that the CRS model may be valid when the residence time of ^{210}Pb in the watershed is much longer than the product of the ^{210}Pb half-life and the watershed/lake area ratio, and that long residence times can be expected where sediment inputs from the catchment are low.

The CIC model, which may also be referred to as the Constant Activity Model, allows the flux to vary and assumes instead that the concentration of ^{210}Pb (Bq kg^{-1}) is constant, or:

$$C_i = \frac{f_i}{r_i} \tag{5}$$

In this model, the flux of ^{210}Pb to the lake bed is assumed to covary with the mass flux in such a way that the initial concentration is a constant. The age of the ith layer is given by

$$t = \frac{1}{\lambda} \ln \frac{c(0)}{c_i(t)}, \tag{6}$$

and the difference in age between two layers is given as

$$t_i - t_j = \frac{1}{\lambda} \ln \frac{c_j(t)}{c_i(t)}, \tag{7}$$

in which the initial concentration cancels. The age of any depth can be calculated based on reference to $C(0)$, which is assumed to be represented by the top of the core. The assumption of constant $C(0)$ is often viewed

as too restrictive to be useful in establishing core chronologies (Sanchez-Cabeza and Ruiz-Fernandez 2012). This concern is valid, but it should be noted that the method may yield useful results even if the initial concentration is somewhat variable. In the most restrictive interpretation of the CIC model, represented by equation 5 above, the initial concentration of ^{210}Pb is assumed to be exactly constant throughout the core. If one assumes that the initial concentration varies slowly throughout the core, the age of the ith layer is given by equation 6 and the difference in age of two layers is:

$$t_i - t_j = \frac{1}{\lambda} \left(\ln \frac{c_j(t)}{c_i(t)} + \ln \frac{c_i(0)}{c_j(0)} \right). \tag{8}$$

When the initial concentrations of the two layers are exactly equal, this reduces to the strict CIC model, applied to adjacent core segments. From equation 8 it follows that a 10% difference in initial concentrations results

in an error in the relative ages of only about +/− 3 years, while a 50% difference results in an error of 13 to 20 years, depending on which initial concentration is higher. While the second term in equation 6 is an unquantified error in practice, since the true initial concentrations are unknown, it demonstrates some flexibility in the CIC assumption.

For Beasley Lake watershed, applying Appleby's criterion for the CRS model (Appleby et al. 1992), the product of half-life and catchment-lake ratio is ~800 years, likely much larger than the residence time of ^{210}Pb in the watershed. Thus, the conditions of a small lake within an agricultural watershed with moderate to high sediment loads and high sediment trapping efficiency favor the CIC model as a more appropriate choice. While the initial concentration of ^{210}Pb in the lake bed is likely not constant, ^{210}Pb deposition will be highly correlated with runoff from the watershed and may be expected to be approximately constant. During runoff events, surficial sediments with adsorbed ^{210}Pb from atmospheric fallout are eroded, transported to the lake, and deposited on the lake bed. A further point to consider is the effect of annual tillage. The mechanical mixing of the upper soil layers due to tillage will homogenize the ^{210}Pb signal derived from eroded material so that an approximately consistent concentration of ^{210}Pb may be achieved from the catchment, even for substantial erosion of surficial soil.

Application of the Constant Initial Concentration Model for Determining Sediment Accumulation Rates. Ages were assigned to BL1 and BL3 using the CIC model to establish relative ages using equation 6 in stepwise fashion through the core. These relative ages must be anchored to some known date in the core to provide a full chronology. The most obvious choice for a known date would be the top of the core, for which there is low uncertainty in date of deposition. Since the first measured ^{210}Pb activity for each core was approximately 1 cm (0.4 in) below the top of the core, $C(0)$ at the top of the core must either be assigned equal to the first measured sample or estimated in another manner. In theory, $C(0)$ can be determined by direct measurement if recent, undisturbed sediment can be collected (e.g., from sediment traps). An alternative method is to use regression of log-transformed ^{210}Pb activities to extrapolate $C(0)$. The regression method, however,

implicitly assumes a constant mass accumulation rate through the core to ensure the log-linear activity profile. If the assumptions of the CIC model are valid, $C(0)$ might also be estimated using an independently dated section of the core, such as from ^{137}Cs. In this method, the ^{210}Pb activity at the depth of the peak ^{137}Cs activity in the core can be used along with the known time interval between core collection and 1963 to estimate $C(0)$. This method assumes only that the present $C(0)$ and the initial concentration at the time of the ^{137}Cs peak are approximately constant (equation 8). If $C(0)$ varies significantly through the core, this method could result in physically unrealistic estimates of $C(0)$ at the top of the core (e.g., $C[0]$ much greater or even much less than the first measured value at ~1 cm depth). While estimating $C(0)$ from the location of the ^{137}Cs peak only provides an estimate of $C(0)$ for the region (unless $C[0]$ is truly constant), in the absence of undisturbed surface sediment samples and given variable sedimentation rates, this method provided the best available estimate of $C(0)$ for each core.

Once ages were estimated for each sample section of the core, sedimentation rates were assigned by using linear regression of the depth versus age plot in three-point segments. This was done to (1) provide some smoothing of the data set while (2) preserving the ability to resolve historical changes in sedimentation rate through the ^{210}Pb activity profile. This is a simplified analogue to the suggestion of Mabit et al. (2014) to use polynomic fits for smoothing CIC based aged estimates of sediment layers. Using three points per segment balanced the goals of preserving valid short-term changes in sedimentation rate while achieving some smoothing in the data.
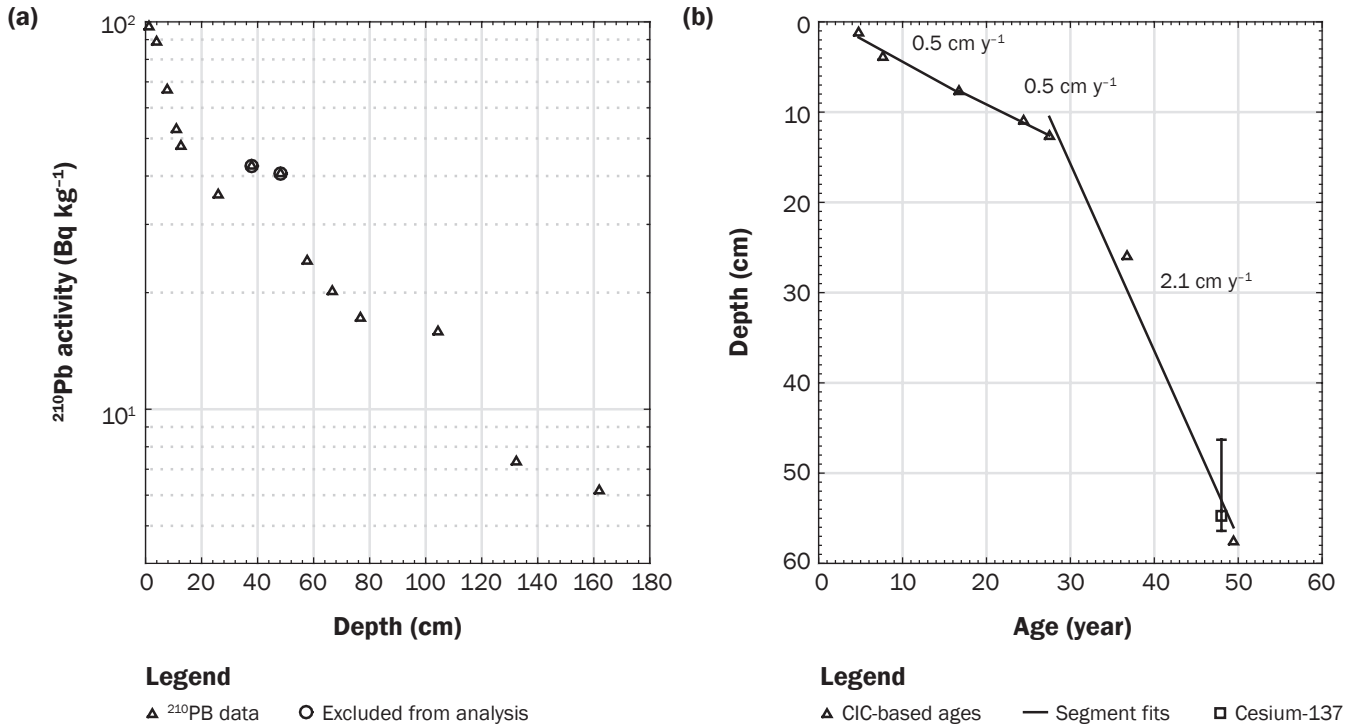
Results and Discussion

Lead-210 activity (figure 3a) and sediment ages determined by the CIC model (figure 3b) for BL1 indicate that sedimentation rates were reduced from 2.1 cm y^{-1} (0.82 in yr^{-1}) to 0.5 cm y^{-1} (0.2 in yr^{-1}) approximately 30 years prior to the 2008 collection date of the core. For BL1, two samples were removed from the analysis, as indicated in figure 3a. The two samples occurred at depths very near the ^{137}Cs peak and, taken at face value, would have resulted in a negative slope in segments of the ^{210}Pb versus depth profile. The agreement of the chronology constructed from the samples immediately

above these samples with the estimated ^{137}Cs depth (figure 3b) suggests that these points were correctly treated as outliers. This approach yielded a similar result to that obtained for the same data in Wren and Davidson (2011), but without imposing an a priori assumption of a breakpoint location in sedimentation rate within the core from knowledge of land use in the watershed. This is a significant improvement in the generality of the methodology and should be much more broadly applicable in studies of agricultural watersheds. The composite rate for BL1 (table 1) is in good agreement with the mean sedimentation rate based on ^{137}Cs data.

The same approach was used to arrive at the results for BL3 (figure 4). A single sample was excluded from the analysis of BL3 to avoid a line segment with negative slope (figure 4a). The calculated rates for BL3 (figure 4b) indicate recent reduction in sedimentation rate, but there was also a period of low sedimentation rate 10 to 30 years prior to 2011. The composite rate for BL3 is in good agreement with the rate obtained from the ^{137}Cs data (table 1) and from the agreement of sediment ages indicated by the ^{137}Cs and ^{210}Pb data shown in figure 4b.

The general trend identified by ^{210}Pb data for BL1 and BL3 is supported by known watershed history and agreement between ages of samples dated by ^{137}Cs. Both sediment cores were collected in the northeast end of the lake, where most of the land has been in the CRP since 2003 (Lizotte et al. 2010). Before that, the land area near the points in the lakes from which BL1 and BL3 were collected was typically planted in either cotton or soybeans (Cullum et al. 2010). Given the variable history of land use for the area surrounding cores BL1 and BL3 and the inability to determine recent sediment accumulation rates at smaller time scales, a direct comparison between effectiveness of erosion control methods in the two areas is not possible.

The time-weighted mean rate, based on ^{210}Pb data, for the top 10 cm (3.9 in; 30 years) of BL3 is approximately 0.3 cm y^{-1} (0.12 in yr^{-1}), which is very similar to the recent rate in both BL1 and BL4. The cause of the discrepancy in historic rates for BL1 and BL3, also indicated by the difference in composite rate seen in table 1, is not known. Without records of land use in the watershed, explanations for this difference would be purely speculation; however, the most

Figure 3
(a) Lead-210 (^{210}Pb) activity and (b) sediment horizon ages and sedimentation rates for core BL1.

(a)

Legend
△ ^{210}PB data   ◯ Excluded from analysis

(b)

Legend
△ CIC-based ages   —— Segment fits   ☐ Cesium-137

important result here is that BL1 and BL3 both indicate that sedimentation rates were reduced dramatically within the last 20 to 30 years. Additionally, the physically reasonable values estimated for $C(0)$ and the agreement of the accumulated segment chronologies with the ^{137}Cs depth/age together provide further evidence that the underlying assumption of the CIC method—that $C(0)$ is approximately constant—is reasonable for this system.

The scatter of the ^{210}Pb data for BL4 (figure 5a) called for a different approach from that used for BL1 and BL3. There was not a viable option for creating a data set with monotonically decreasing ^{210}Pb activity for BL4. The recent ^{137}Cs activity shows some evidence of scatter, but older ^{137}Cs data do not. The lack of scatter and consistent decrease of ^{210}Pb with increasing depth displayed in the first three points indicated that they should be grouped together. The second group of points began with the third highest point and included all points below it. This approach minimizes the impact of the scatter and arrives at a composite picture of sedimentation rate for BL4 (figure 5b), which is in agreement with the mean rate indicated by ^{137}Cs. The different trend in sedimentation rate, with a sharp decrease in sedimentation

rate in approximately 2001, may be due to the proximity of BL4 to a point of entry for concentrated flow from the watershed.

No logical grouping for the ^{210}Pb data for BL6 was found (figure 6a), so the average rate from ^{210}Pb was estimated by a linear fit to the entire set of data (figure 6b). This approach yielded a sedimentation rate that is much higher than that indicated by ^{137}Cs (table 1) for the same core. Of the four cores discussed here, only the ^{210}Pb data from BL6 did not yield useful information. It was decided to present the data, since part of the aim for this manuscript is to demonstrate the use of radioisotope dating in a watershed where frequent inputs of sediment into

the receiving lake complicate the use of the data. BL6 demonstrates a ^{210}Pb profile that is not amenable to detailed analysis aimed at identification of shorter term trends in sedimentation rate.

A significant difference in the approaches applied here, relative to that used in Wren and Davidson (2011), is that no attempt was made in the present work to match a breakpoint in the data with a specific time of change in the watershed. This makes the approach more generally applicable across a variety of situations, since information about watershed history is not necessary for application of the methodology. In the end, where the ^{210}Pb data are noisy, there is a limit

Table 1
Summary of sedimentation rate data.

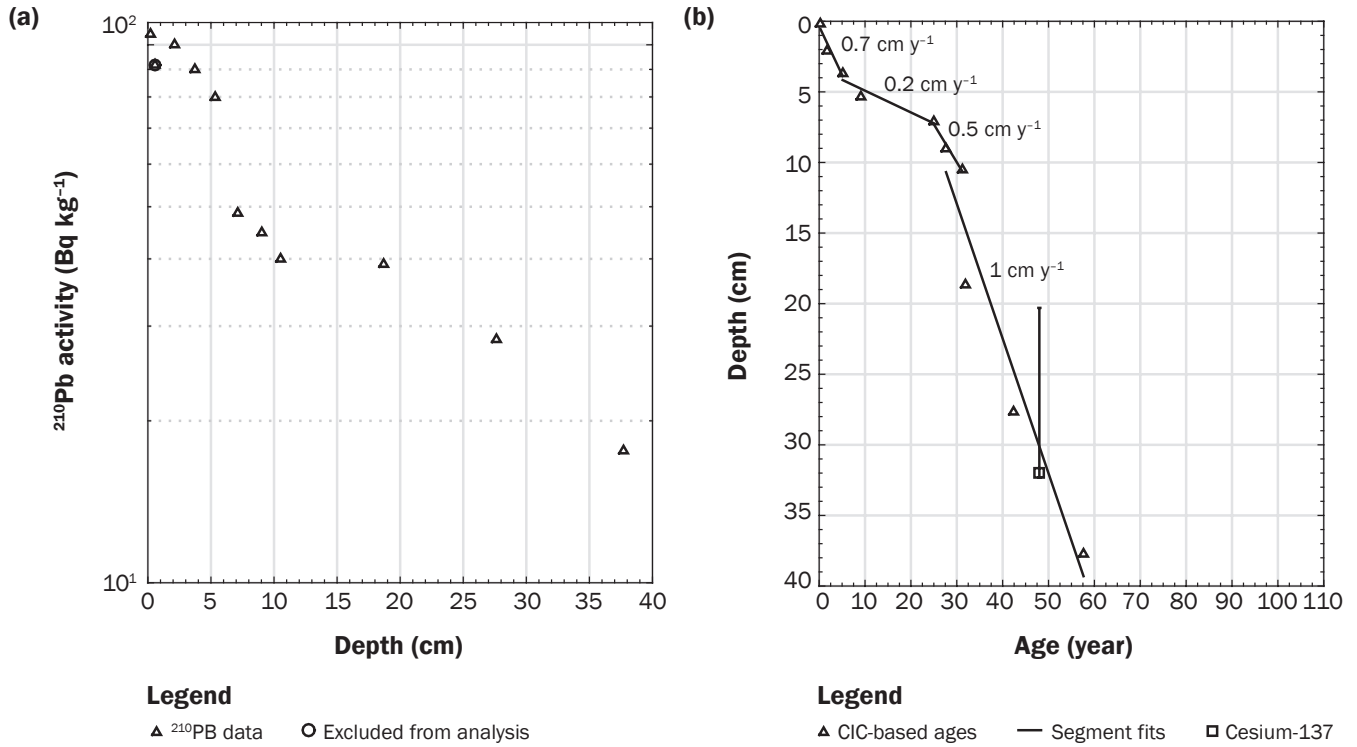| Core	Mean rate from ^{137}Cs (min-max) (cm y^{-1})	Approximate breakpoint year	Recent sedimentation rate (cm y^{-1})	Historic sedimentation rate (cm y^{-1})	Composite rate from ^{210}Pb segments (cm y^{-1})
BL1	1.0 to 1.2	1979 to 1989	0.5	2.1	1.2
BL3	0.4 to 0.7	1971 to 1991	0.3	1	0.5
BL4	0.9 to 1.1	1996 to 2006	0.2	1.3	1.3
BL6	0.7 to 0.9	n/a	n/a	n/a	n/a

Notes: ^{137}Cs = cesium-137. ^{210}Pb = lead-210.

Figure 4
(a) Lead-210 (^{210}Pb) activity and (b) sediment horizon ages and sedimentation rates for core BL3.

(a)

Legend
△ ^{210}PB data   ○ Excluded from analysis

(b)

Legend
△ CIC-based ages   — Segment fits   □ Cesium-137

Figure 5
(a) Lead-210 (^{210}Pb) activity and (b) sediment horizon ages and sedimentation rates for core BL4.

(a)

Legend
△ ^{210}PB data   — Top segment   - - Bottom segment

(b)

Legend
— Segment 1   — Segment 2   ---- Extrapolated   □ Cesium-137
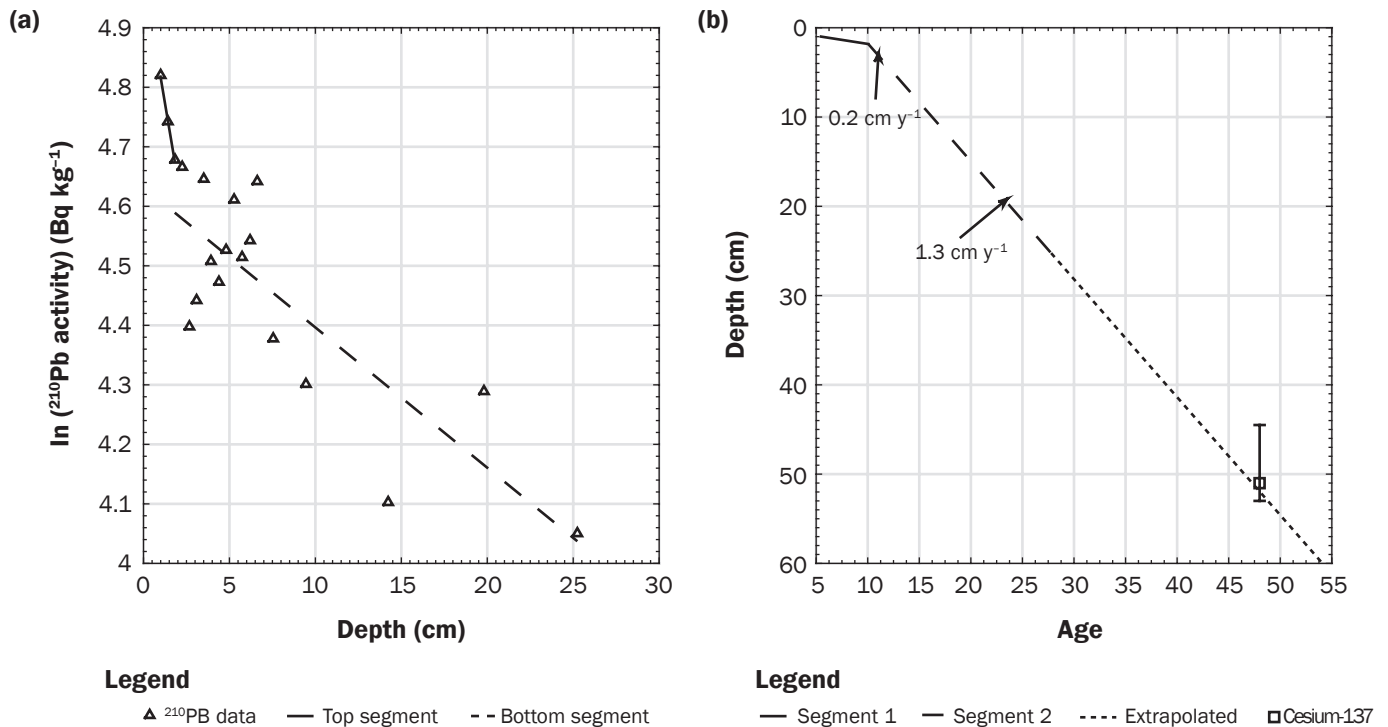
Figure 6
(a) Lead-210 (^{210}Pb) activity and (b) sediment horizon ages and sedimentation rates for core BL6.

Legend

○ ^{210}PB data   — Linear fit

Legend

— Ages from fit to ^{210}Pb data   □ Cesium-137
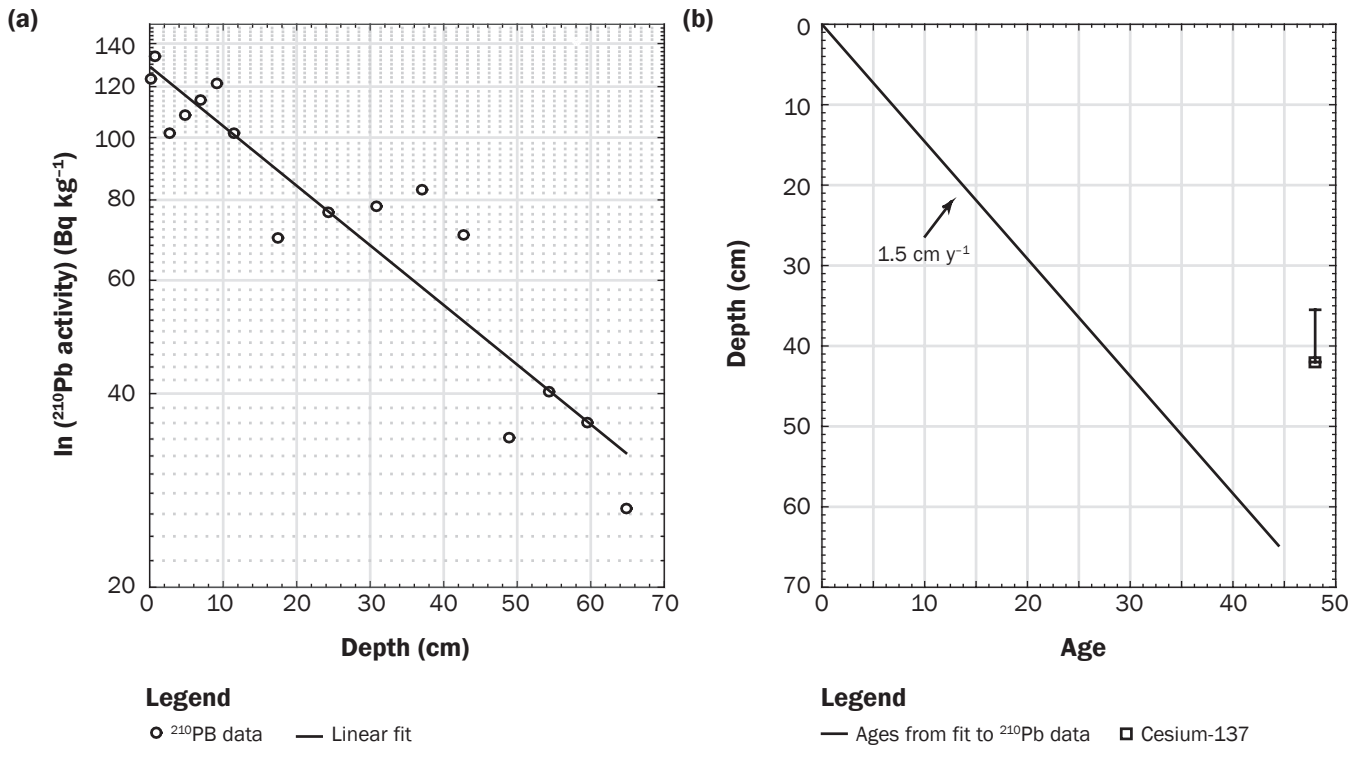
to the information that can be gleaned. One simple recommendation that comes out of this study is, if possible, to collect multiple cores from a lake. This will allow comparison and higher degree of certainty in the results. In the case of Beasley Lake, adding multiple cores added more nuance to the results that were previously reported in Wren and Davidson (2011). For example, the earlier study showed a clear breakpoint in the sedimentation rate; it was assumed that the same sedimentation regime was consistent across the lake's area. The new data show that the reduction in sedimentation rate is most clearly expressed in open water far from sediment inputs.

The reduction in recent sedimentation rates estimated from the core is consistent with data from other studies in the watershed since the mid-1990s. Lizotte et al. (2014) found that, over the time period 1996 to 2009, there were significant reductions in total suspended solids that could be linked to changes in watershed management described previously. Based on suspended solids data described in Lizotte et al. (2012), a recent sediment accumulation rate on the order of 0.1 to 0.2 cm y^{-1} (0.04 to 0.08 in yr^{-1}) since 2001 is possible, lending weight to

this explanation. Cullum et al. (2010) documented reductions in sediment and nutrients resulting from conversion of land to CRP in 1995 to 2008 and found that conversion of land to CRP was more effective at reducing sediment loading to the lake than reduced tillage farming practices.

While mixing and resuspension by wind can be an important consideration in lake sediments, the effect in Beasley Lake is likely to be minimal. Bloesch (1995), Peterson (1999), and others discuss the importance of and mechanisms for sediment resuspension in lakes. The most important driver for resuspension is wind acting on water surface (Bloesch 1995). Using equations 1 and 2 from Carper and Bachmann (1984) with a wind speed of 10 m s^{-1} and a maximum fetch of 1,200 m (3,937 ft), a wavelength of 1.4 m (4.6 ft) can be estimated for Beasley Lake. The wave base, taken to be one-half of the wavelength, is at approximately 0.7 m (2.3 ft). More than 80% of the lake has a depth of 1.2 m (3.9 ft) or greater, and nearly all of the lake along the maximum fetch is greater than 2 m (6.5 ft) in depth. Beasley is sheltered by trees on all sides, although there are fewer trees on the south and west than elsewhere.

Given these constraints, it is unlikely that resuspension is a significant factor.

Many land management practices that reduce sediment accumulation rates are based on slowing runoff to reduce the energy of flowing water, which allows coarse particles to settle out and be trapped. The result of this process should be a fining of particles from near-surface core increments relative to those deeper in the core that were deposited before land management practices mitigated soil erosion. Figure 7 shows the results of particle size analysis for core BL3. The increase in clay content and decrease in silt suggests that this process was at work in Beasley Lake. The increase in clay content at a depth of 20 to 25 cm (7.9 to 9.8 in) places the time of transition in particle size in approximately 1970 to 1990 according to the chronology of core BL3 in figure 4b. There is little or no documentation for land use in the watershed before the early 1990s. Given the lack of information, an explanation for this early reduction in particle size is difficult; however, the continued low levels of silt and sand entering the lake may, at least in part, be attributed to the same processes that caused the reductions in sediment accumulation rate that have been

Figure 7

Particle sizes for core BL3. A rapid shift in clay and silt percentages of approximately 10%, towards coarser composition, occurs at a depth of 20 to 25 cm consistent with declining coarse sediment delivery to the lake.

Legend

−□− % sand   −●− % silt   --○-- % clay
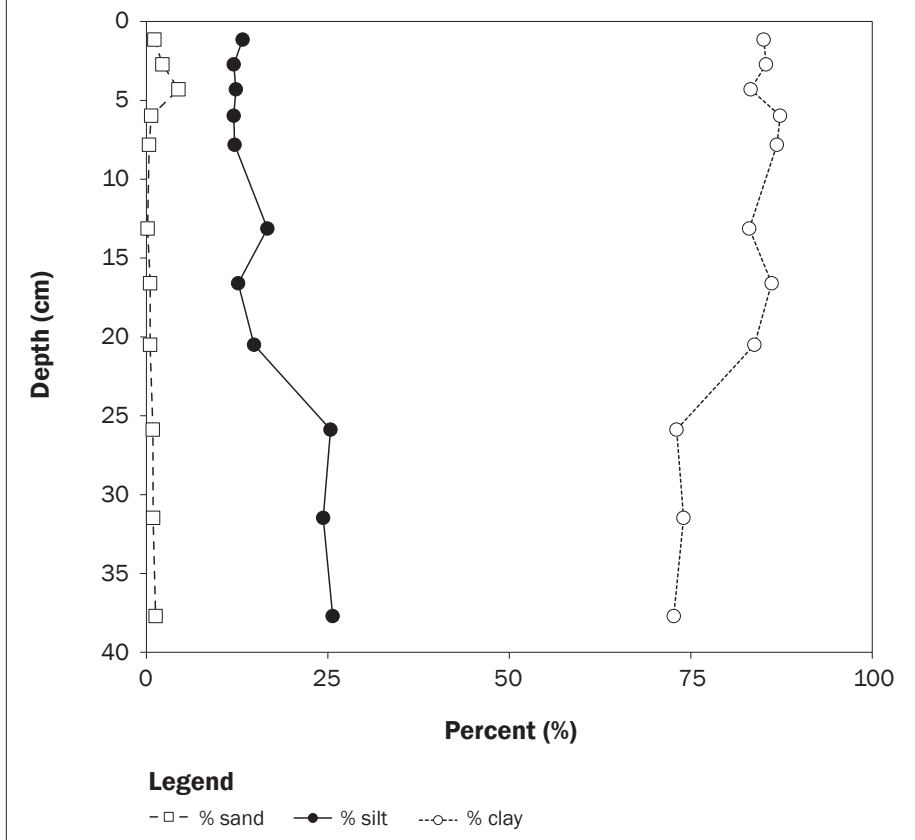
documented here. The lower fall velocity of fine particles resulted in more time spent in the water column before deposition. This increase in time spent in the water column increased the likelihood that particles were mixed throughout the lake and distributed over the entire lake bottom. Homogenously deposited sediment particles make detection of local changes in sediment accumulation rate unlikely.

Summary and Conclusions

Sedimentation rates from radiometric analysis of three new sediment cores and one core from a previous study, all collected from Beasley Lake, Mississippi, were analyzed using a modified form of the CIC model for ^{210}Pb dating. The CIC model was applied using the assumption that initial ^{210}Pb activity varied little through the core, making it possible to apply the model to find the time that passed between the deposition of adjacent sediment layers. An asymmetric bi-Gaussian distribution was fit to the ^{137}Cs depth profile to estimate the depth of the

^{137}Cs peak from limited data, and the average rate of sedimentation calculated from the ^{137}Cs peak was compared to composite rates that were derived from ^{210}Pb analysis. For the three cores where the ^{210}Pb data yielded multiple segments of different sedimentation rate, the age of the sediment horizon dated by ^{137}Cs was in good agreement with the age identified by ^{210}Pb segments. The finding of reduced rates of sedimentation in Beasley Lake agrees with both land use changes and data from other recent studies in the watershed.

The collection and analysis of four cores from the same lake yielded information on the potential uncertainty of the results and importance of site selection for obtaining useful cores. Two of the four cores yielding well-behaved ^{210}Pb and ^{137}Cs profiles (BL1 and BL3) were located near the center of the lake and furthest from any point sources of runoff from the watershed and, while agreeing broadly in their sediment accumulation histories, differed in detail. BL4 displayed substantial scatter in ^{210}Pb in a section of the

core approximately 2 to 7 cm (0.7 to 2.7 in) from the surface. As ^{137}Cs levels do not vary significantly over those depths, it is possible that a portion of the upper sediments were mechanically disturbed prior to sampling. The final core, BL6, neither yielded a monotonically decreasing ^{210}Pb profile, nor showed evidence of disturbance.

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