Supporting Online Material

Title: Natural streams and the legacy of water-powered mills
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Materials and methods

Phosphorous, Nitogen & Carbon Analyses and Carbon Sink Estimates

Carbon and Nitrogen Concentrations by Elemental Combustion Analysis (ECA)

Elemental combustion analysis for total carbon and total nitrogen in solid-phase samples (plant tissue, soils, sediments, etc.) is based on the transformation of C and N to gas phases by extremely rapid and complete flash combustion of the sample material, and measurement of elemental concentrations via gas chromatography (GC).

A Costech ECS 4010 CHNS-O system was used for this study. It was calibrated by analyzing five solid-phase reference materials at the beginning of each run, and at fixed intervals thereafter (usually one reference standard per ten unknowns.)

Ultra-high purity acetanilide (four samples in ca. 0.25, 0.50, 0.70 and 1.00 micrograms increments) and atropine (at ca. 0.1 micrograms) were used to generate the calibration curve; total C and total N contents were calculated from stoichiometry.

A rotating autosample changer delivers one tin-encapsulated sample at a time into the top of a quartz combustion tube. This tube contains granulated chromium III oxide combustion catalyst and is held at 1000 °C. A pulse of pure O_2 is admitted with each sample. The thermal energy created during flash combustion of the ultra-pure tin capsule and the sample in a pure O_2 environment generates an instantaneous temperature of ~1700 °C. All combustible materials in the sample are burned and the resulting gas-phase combustion products are swept out the bottom of the furnace by a constant stream of non-reactive helium carrier gas.

All carbon in the sample is converted CO_2 during flash combustion. Nitrogen-bearing combustion products include N_2 and various oxides of nitrogen NO_x; these pass through a reduction column filled with chopped Cu wire (600 °C) in which the nitrogen oxides give up their oxygen to the copper and emerge as N_2.

Water vapor from the sample is removed by a gas trap containing magnesium perchlorate. If the samples are being analyzed for nitrogen only, CO_2 is removed by a second gas trap containing a CO_2 scrubber (sodium hydroxide on silicate carrier granules).

Empty tin-capsule blanks are included ever tenth sample, and detectable N or C was subtracted from the sample and standard values to give a zero baseline.

Phosphorus Concentrations by Inductively Coupled Plasma Optical Emission

The EPA Method 3051 was used to partially digest 0.2500 ± 0.0002 g of crushed sediment samples in 10 mL of concentrated nitric acid heated to 175°C in a CEM MARS Xpress microwave digestion system. The digestate was filtered and diluted to 50 mL, resulting in a 20% HNO_3 solution.

Concentrations of 14 trace elements (Al, Ba, Be, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, P, Pb, and Zn) were measured by ICP-OES on a Spectro Ciros CCD instrument connected to a Hewlett Packard computer running Smart Analyzer Ciros CCD software. The spectrometer was calibrated with five calibration standards and a blank (20% HNO_3) during each run. The standards are made from the initial solutions, using Pyrex glass volumetric flasks and ~6 Mega-Ohm distilled water. Volumes are measured using Fisherbrand Finnipipettes of 2-10 mL, 1-5 mL, and 100-1000 µL sizes and Finntip 10 mL and 5 mL and Fisherbrand 101-1000 µL pipette tips. Standard analytes were stored in Nalgene bottles, and used within 10 days of preparation.

After the calibration natural (rock and soil) standards are measured at the beginning, middle, and end (or at appropriate intervals for large batches) to check the consistency of the measurements. If a significant change occurs in the measured values of the standards, the instrument was recalibrated. Trace elemental compositions of each digested soil solution measured three times by the spectrometer and an average and standard deviation are calculated, printed, and stored in a data file on the computer.

Carbon, Nitrogen, and Phosphorus Contents of Stream Banks

Our analyses of stream bank sediments from five watersheds in four counties and two physiographic provinces of Pennsylvania are summarized in Table S1. These data show average N concentrations ranging from 400-2100 ppm (overall mean = 1160 ppm), which equates to a loading of 0.8 to 4.3 lbs N/ton of eroded sediment. The concentrations of P in stream banks range from 340-958 ppm (overall mean = 556 ppm), which equates to 0.7 to 1.9 lbs P/ton of eroded sediment. The concentration of stream bank P is generally lower and more consistent from site to site than N, which might reflect: (1) different physical and chemical properties of P and N; (2) historical land use activities that might have caused historical nutrient enrichments within the watershed (e.g., fertilizer application during the 19th and 20th Centuries); and (3) the transport mechanisms that redistributed these “legacy nutrients” and stored them in valley bottoms. Detailed analyses are available on request.

Carbon Sink Calculations

The average dry mass bulk density for aggregate stream bank sediments (pre- and post-settlement sediments) is 1300 kg/m^3 (measured range from 900 to 1500 kg/m^3), with an average organic carbon content of 1.5 wt.% (15,000 mg carbon per kg of sediment). The average thickness of stream bank deposits is ca. 2.0 m.

Multiplying the fraction of carbon in the sediment (0.015) by the bulk density (1300 kg/m^3) by the depth analyzed (2.0 m) yields:

$$0.015 \text{ carbon} \times 1300 \text{ kg/m}^3 \times 2.0 \text{ m} = 39.0 \text{ kg carbon/m}^2$$

One hectare is 10,000 m^2:

$$39.0\ \text{kg/m}^2 \times 10{,}000\ \text{m}^2 = 3.90 \times 105\ \text{kg/ha}$$

One tonne (T) is 1,000 kg:

$$3.90 \times 105\ \text{kg/ha} \times 1{,}000\text{-}1 = 390\ \text{T/ha}$$

Table S2 lists representative carbon storage values for the range of measured carbon contents and bulk densities. These values are in keeping with wetland and agricultural soil carbon densities around the world, as noted by others (*S1*, *S2*).

Cesium-137 Analyses

Here we use a ^{137}Cs inventory to document the relative contributions of sediment from two main landscape sources in a small agricultural watershed, Big Spring Run (West Lampeter Township, Lancaster County, PA).

Cesium-137 concentrations were derived by gamma spectrometry on stream bank sediment profiles, on upland soils, and on suspended sediment in the stream itself. Analyses were conducted by J. Ritchie (USDA), with the analytical procedures and calculations as outlined by (*S3*): (1) upland agricultural slopes and (2) stream banks in valley bottoms. An inventory of fallout ^{137}Cs activity from two hill slope transects adjacent to Big Spring Run yield average post-1963 erosion rates of 1.8 t/ha/yr (3.9 t/acre/yr) and 0.3 t/ha/yr (0.7 t/acre/yr), both of which are significantly less than the presumed average county-wide erosion rate of 4 t/ha/yr (8 t/acre/yr). These values, however, agree with our additional study of erosion rates in the watershed using the revised universal soil loss equation and GIS interpretation of aerial photographs flown over the past 60 years. This study indicates a dramatic reduction in soil erosion rates from ca. 25 t/acre/yr in 1940 to ca. 5 t/acre/yr in 1988, and which remains under 5 t/acre/yr to 2005. Although even this lower value indicates soil mobility on the landscape, we do not know how much of this sediment reaches the stream. However, the average contribution of sediment supplied to Big Spring Run from bank erosion can be deduced using mass balance calculations of the ^{137}Cs data. Our results show that roughly 30% to 80% of the sediment supplied to this watershed can be accounted for by bank erosion (*S4*).

Lead-210 Analyses

Lead-210 is a naturally occurring isotope in the long-lived ^{238}U decay chain. Uranium is a present in trace amounts in most rocks and soils. Within this U decay chain, ^{210}Pb is derived from the decay of ^{226}Ra ($T_{1/2}$ = 1600 yr) via ^{222}Rn ($T_{1/2}$ = 3.8 d). Disequilibrium arises when a small portion of the gaseous ^{222}Rn diffuse through the soil to the atmosphere, where it decays to ^{210}Pb. This “unsupported” ^{210}Pb attaches to water molecules and falls to Earth during precipitation where it becomes adsorbed onto fine-grained soil and sedimentary particles. The 22.3 yr half life of ^{210}Pb makes it suitable for dating sediments deposited within the last 100-150 years (*S5*), or in this case, determining which stream bank sediments are older than ca. 150 years.

Lead-210 analyses were performed at Case Western Reserve University (through the courtesy of G. Mattisoff and A. Stubblefield). Two gamma spectrometers were employed: an EG&G Ortec N-type HPGe detector system and a Canberra Low Energy Germanium Detector (LEGe) system. Samples were sealed in plastic Petri dish containers for several weeks, placed on the gamma detector, and counted for 23 hr: “unsupported” ^{210}Pb was measured at 46.52 keV. The net ^{210}Pb counts were corrected for sediment self-attenuation, detector efficiency, branching ratio, and radioactive decay since the sample was collected and sealed (for methods, see *S6*).

Radiocarbon Dating

Except where noted in Table S3, all analyses were performed by Beta Analytic, Inc., using either scintillation counting (referred to as conventional or standard radiocarbon dating), or by accelerator mass spectrometry (AMS). Thirty-nine dates were provided by Dr. Fred Kinsey, professor emeritus at Franklin and Marshall College Department of Anthropology.

Materials measured by the radiometric technique are analyzed by synthesizing sample carbon to benzene (92% C), measuring for ^{14}C content in a scintillation spectrometer, and then calculating for radiocarbon age. AMS results are derived from reduction of sample carbon to graphite (100% C), along with standards and backgrounds. The graphite is then measured for ^{14}C in an accelerator-mass-spectrometry.

The “Conventional C^{14} Age” is the result after applying C^{13}/C^{12} corrections to the measured age and is the most appropriate radiocarbon age (Table S3). Applicable calendar calibrations are included for organic materials and fresh water carbonates between 0 and 20,000 BP.

Hydraulic Geometry and USGS Gage Station Data

United States Geological Survey (USGS) gage station data for discharge and suspended sediment load for the Chadds Ford gage station on the Brandywine Creek are available at http://waterdata.usgs.gov.

Supporting text

Selections of historical evidence and descriptions of early European-American mill damming on the Brandywine

1. Darlington, William M., 1893, Christopher Gist’s journals with historical, geographical, and ethnological notes and biographies of his contemporaries: J. R. Weldin and Company, Pittsburgh. [Transcription below is verbatim, with sentences about areas other than the Brandywine removed from beginning of excerpt. Gist (1706-1759) was an early American explorer.]

> “December 7 [1751].—…the well known Delaware, Nemacolin.…was the principal of the Indians employed by Gist and Cresap to blaze and clear the road before mentioned. He was intelligent and trustworthy. (Jacobs' "Life of Cresap," 1828, p. 28.) A letter from his father, Checochinican, the chief of the Indians on the Brandywine, to Governor Gordon, June 24, 1729, is in the "Pennsylvania Archives," Vol. I, p. 239. It seems the Indians had sold their lands on the Brandywine, reserving a part on the head of the creek, by a writing, which was burned, with the cabin

> wherein it was deposited. The mill-dams of the white settlers destroyed their fishing, and they were otherwise "crowded out "—as usual to the present day. (See "Pennsylvania Archives," Vol. XII, p. 281. "Colonial Records." Vol. III, p. 269. "Votes of Assembly," 1726, Vol. II, p. 481. Smith's "History of Delaware County," pp. 235, 240. Gordon's "History of Pennsylvania," p. 194. Hazard's Pennsylvania Register," Vol. I, p. 114.)"

2. The statutes at large of Pennsylvania from 1682 to 1801 / compiled under the authority of the Act of May 19, 1887, by James T. Mitchell and Henry Flanders, commissioners; v. VII, 1765-1770: Harrisburg Publishing Co., State Printer, Harrisburg, PA. [Excerpt below is verbatim, with some material omitted for brevity, from Chapter DLXXVIII, yr 1767-68, p. 193-196.]

> "An act for regulating the fishery in the River Brandywine.
>
> Whereas it hath been represented to the assembly by petition from a number of the freeholders of the county of Chester that live on or near the river called Brandywine that their ancestors, themselves and the poor adjacent inhabitants have formerly enjoyed great advantages from the fishery in the same river; and although no person owning lands below the fork or main branches can claim any right by survey to the lands covered with the waters thereof, yet divers persons have erected dams across the said river, to the almost total obstruction of the fish running up the same:
>
> Wherefore [for] remedying the mischiefs aforesaid:
>
> [Section I.] Be it enacted by the Honorable John Penn, Esquire, Lieutenant-Governor under the Honorable Thomas Penn and Richard Penn, Esquires, true and absolute Proprietaries of the Province of Pennsylvania and counties of Newcastle, Kent and Sussex upon Delaware…That all and every person and persons whatsoever having already erected or that shall hereafter erect any mill-dam or other obstruction across the said river below the forks thereof within this province shall make, open and leave the space of nine feet in breadth near the middle of the said dam at least fourteen inches lower than any other part thereof, so that there be at least twelve inches depth of water during the months of March, April and May in every year constantly running through the same; and for every foot that the dam is or shall be raised perpendicular from the bottom of the said river there shall be laid a platform either of stone or timber or of both, with proper walls on each side to confine the waters, which shall extend at least four

> feet down the stream, and of the breadth aforesaid, to form a slope for the water's gradual descent; and that all and every person and persons who shall refuse or neglegct to make or alter his, her or their dams in the manner directed as aforesaid within the term of one year next after this act shall be in force, every such person so offending…shall forfeit and pay the sum of one hundred pounds…or suffer nine months' imprisonment..."
>
> [Act passed February 20, 1768.]

3. Text below is a brief history of early milling industry in the Chadds Ford area, Brandywine River, PA, written by Elizabeth Rump, Site Administrator, Brandywine Battlefield Historic Site. [Source: http://www.chaddsfordhistory.org/history/industry.htm; accessed August 10, 2007]

> ""TO Be SOLD by the Subscriber, A VALUABLE MERCHANT MILL and SAWMILL ....Benjamin Powell."
>
> "TO BE SOLD, A Good Merchant Mill, and Sawmill, all in good Repair with a good sufficient Dam, on Little Brandiwine...John Buchanan."
>
> JONATHAN VAUGHAN, and JOHN CHAMBERLAIN, having purchased the Rights of Dennis Whealen, and Doctor Kennedy, in Serram Forge Mills...."
>
> (From The Pennsylvania Gazette, November 14, 1781, March 15, 1764, and May 27, 1762, respectively.)
>
> Grist Mills, Saw Mills, Paper Mills, Fulling Mills, Oil Mills, Iron Furnaces and Forges - it's no accident that Chester and Delaware Counties were home to many early industries. … [text omitted] The large agricultural sector provided the grain to be ground, the flax seed to produce linseed oil, and wool for fulling. Natural resources, too, were available for the taking: timber, iron ore and limestone. Add to the above easy access to ready markets in Philadelphia, Wilmington, and Baltimore and you have a "receipt" for success. In fact, "by 1760, Bucks, Chester, and Philadelphia Counties contained over 160 grist mills." (History of Concord Township, p.92).
>
> The earliest mill in Pennsylvania was reportedly begun by Richard Townsend in Concord Township in 1683, and run by Caleb Pusey, the "Governor's Miller." By 1694 there were five mills listed on the tax records in Concord Township. In 1790, there were seven saw mills, two grist mills, and one paper mill in Concord Township alone. Included among this number was the grist mill started by Nathaniel Newlin in 1704, called Newlin Mill today.

> According to tax records for the year 1796 in nearby East Bradford Township there was one fuller, three millwrights and six millers. In 1850 there was one paper mill, five millers and five saw mills. Strode's Mill, at the intersection of Birmingham and Lenape Roads, began operation in 1721. Known at Etter's Mill, it was operated by J.C. Etters. The business was purchased by the Strode family in 1737, and remained in the Strode family for 150 years. In addition to grinding grain it was also used as a saw and cider mill.
>
> Locally, Francis Chadsey, father of John Chads, erected a corn mill c. 1710. Other entrepreneurs followed his lead: James Huston in 1719; Joseph Taylor in Pocopson in 1724; and Joshua Sharpless paid taxes on a saw mill situated along Radley Run in 1787. William Twaddell operated a paper mill in 1777, which had additional uses as a saw mill, a combined iron works and saw mill, and a powder mill. Also nearby, Benjamin Ring established a grist, fulling and saw mill along Harvey's Run prior to the Revolutionary War.
>
> The first paper mill in the colonies was erected by Wilhelm Rittenhouse in 1690 near Germantown. In addition to Twaddell's paper mill, mentioned above, a Mr. Wilcocks operated a paper mill in Concord Township at the time of the American Revolution. … [text omitted] Although not as prolific in this area as mills, furnaces and forges also dotted the landscape along Crum Creek (Peter Dicks), Sarrem Forge (c. 1742) of John Taylor along Chester Creek, Joseph Buffington along the Brandywine, as well as those more popularly known today such as Warwick Furnace, Hibernia, and, a bit farther afield, Joanna and Hopewell."

[Note: Early American forges, blacksmith shops, and furnaces also built dams to harness water power to run bellows and machinery.]

4. Summary of early milling history of Chadds Ford, PA, on the Brandywine River west of Philadelphia. Text is verbatim from source. [Source: Susan Hauser, Chadds Ford Historical Society. http://www.chaddsfordhistory.org/history/worldofjc/whojc.htm, accessed August 5, 2007]

> "Sometime prior to February 1683, Francis Chadsey and his wife, the widow Hester Coaleman Davis, arrived on these shores from Wiltshire, England…In 1702, the Chadsey family "removed" to Burmingham (Birmingham) Township where Francis had purchased a 500 acre plantation of good meadow and upland. Within a year's time, he had built a mill, probably a log structure, on the

> banks of the Brandywine Creek. It was a corn mill which, in the English tradition, means that grains -- wheat, oats, and barley -- were milled there.
>
> …[in 1713] Francis Chadsey died, leaving his plantation and half of his mill to John, "when he comes of age." [His wife] must have continued to operate the mill after her husband's death. That same year she signed a nine-year agreement for water rights "extending one and forty perches" [~200 m] on the Brandywine…"

5. Historic records of mill crowding in Delaware along the lower Brandywine River. An archaeological report for the Delaware Department of Transportation describes a system of cooperative power exploitation:

> "Power system management required cooperation among mill owners, who jealously guarded their individual rights to the resource. Brandywine mill owners, for example, formed a mill seat company that briefly (1813 to 1829) attempted to control the stream's power.... Such combinations on other fall line sites, notably at Paterson, New Jersey, and Lowell, Massachusetts, created industrial power systems around communal races….On a smaller scale, the power of Pike Creek was harnessed by a cooperating group of mill owners.
>
> On [nearby] Red Clay, Pike, and White Clay creeks, each mill owner managed his own water power source, even when the races actually overlapped one another. *The mills were so closely spaced that the foot of one tailrace was in effect the head of the next impoundment downstream*". [italics added]

Source: Burrow, Ian, Liebeknecht, William, Ferenback, Susan, Heite, Edward, and Wicks, Carolann, 2003, Archaeological and historical research on Henderson Road/Old Coach Road, Mill Creek Hundred, New Castle County: Delaware Department of Transportation Archaeology Series no. 164. [Source: http://www.deldot.gov/static/projects/archaeology/henderson_road/, accessed August 4, 2007]

Historic paintings of mills, mill dams, and mill ponds along the Brandywine

Numerous historic landscape paintings and illustrations of the Brandywine valley, including those from the "Brandywine School" of artists are replete with examples of mill buildings, mill dams, and mill ponds.

The *View of the Brandywine: Gilpin's Paper Mill*, by Thomas Doughty, for example, was completed in the late 1820s and is owned by the Brandywine River Museum. [The Museum itself is housed in a former grist mill on a mill site that dates to the late 1600s, and is located several hundred meters downstream of the breached mill dam that provided water to the mid-1800s mill building.] Doughty's landscape painting of Gilpin's Mill, a paper mill that was located along the lower reach of the Brandywine just north of Wilmington, Delaware, is considered by the Museum to provide "excellent documentation regarding the rural appearance of the lower Brandywine Valley during that period" (Brandywine River Museum News, August 2005, #35). The painting shows a large pond and a long mill dam near the mill building. The first mill on the site was established by Joshua Gilpin and his uncle in 1787. The pond no longer exists, and the mill ceased operation in the mid-1800s.

Brinton's Falls, painted by Brandywine Valley artist N. C. Wyeth (1882-1945), shows the Brandywine River flowing over one of the two mill dams at Brinton's mill site (original mill built on the site in 1706), which now is owned by the Wyeth family.

See also landscape paintings by Bass Otis (1764-1861) and Robert Shaw (1859-1912), some of which are available as on-line images at the Brandywine River Museum at

http://brandywine.doetech.net/voyager1/Results.cfm?ParentID=126270

Historic photographs of mills, mill dams, and mill along the Brandywine

"Along the Brandywine River" by Bruce Edward Mowday (2001, Arcadia Publishing) contains numerous historic photographs of mills, mill dams, and mill ponds that were used in postcards in the late 1800s and early 1900s.

For example, p. 15 describes an early 20th c. photograph of a large mill pond (with boaters) in the headwaters of the East Fork of the Brandywine:

> "The Brandywine passes through Cupola, where a dam once held back the Brandywine in the northern region of the east branch of the river. An old gristmill on one of the properties surrounding the river was powered by the Brandywine. The mill had long since ceased functioning and had been turned into a home. The large pond made by the dam was a local favorite of young ice-skaters during the winter."

Page 12 describes a photograph (pre-1908) of an early mill building:

> "…the Brandywine valley was a working community in the early 1900s. Farms used the Brandywine and its tributaries to feed the livestock. The mill pictured is one of many that flourished in the area because of the Brandywine. The mill fueled the local economy and contributed food to the hungry troops at Valley Forge during the long winter of 1777-1778 [during the Revolutionary War]."

Page 17 shows a pre-1913 photograph of cottages and cabins with boat docks along the edge of a lake formed by Kurtz's dam (from a pre-existing mill site), which is illustrated in a second photograph (also early 1900s) on the same page.

Pages 18-19 show the large lake formed by Kurtz's dam, and describe a boat club that, like the lake, no longer exists. Parts of the captions of these photographs are excerpted below:

> "…this 1907 postcard says "View at Kurtz's Dam, Coatesville, Pa." The cabins at the dam can be seen in the background….few modern-day residents of Coatesville remember the boat club….the cottages…and the dam itself are only memories…only the Brandywine flows as a reminder of a bygone day of the city of Coatesville."

Pages 85-109 contain multiple early 20th c. photographs of mill buildings, stone mill dams that span the entire valley bottom, races, and mill ponds along the lower Brandywine, between Chadds Ford, PA, and the river's mouth at Wilmington, DE, a reach of the river heavily impacted by milling that dates to the early 1700s and, in some cases, even the late 1600s. Examples are excerpted from captions of several images below.

> "Rockland Paper Mill, on the Brandywine …A dam was built in Rockland to aid the generation of power. William Young started his paper mill at Rockland in the late 1700s." (p. 85)
>
> "The DuPont fortune was made on the banks of the Brandywine with gunpowder mills…The pair of black powder du Pont mills shown in these postcards were constructed from 1822-1824 and are called "the Birkenhead". These mills produced powder for 117 years…The mills ceased operation in 1921, and the mills are now part of the Hagley Museum along the Brandywine River just north of Wilmington [Delaware]." (p. 86-87)
>
> "Downingtown did not have the only paper mills on the river. Delaware had the Augustine Paper Mills, near the city of Wilmington….the card below depicts the dam that aids the work at the mill. The dam is located above Riddle's and Augustine Mills." (p. 91)
>
> "…the famous Canby Vista in Rockford Park….Oliver Canby built the first gristmill on the lower Brandywine in 1742." (p. 92)

Global historic data on mills and dams

We have compiled a sampling of quotes from various compilations of historic material that document the ubiquity, pervasiveness, and global spread of mills and milling technology. Many scholarly works in archaeology, history of technology, medieval history, and other disciplines document the spread of watermills and dams throughout Asia, the Mid-East, Europe, North America, and other parts of the world during the past two millennia. As milling technology progressed, millers and millwrights developed increasingly efficient means of harnessing greater amounts of water power. This progression led, in general, from the horizontal to vertical wheel, and from the vertical undershot (water flowing under the rotating wheel) to overshot (water flowing across the top of the rotating wheel) wheel. The overshot wheel generally requires a greater hydraulic head, so higher dams and longer mill races were used more frequently after the 12th century (*S7*). As mills multiplied, several mills used the same reservoir (and hence dam), as in cases where mills were located along a single race.

Our research in the eastern US indicates that increasingly higher dams were built at the same sites over a period of several centuries, and we find multiple instances of buried dams and sediment-filled ponds within larger sedimentary wedges. It is likely that the same phenomenon occurred in places where milling played an important role for many more centuries. If so, the accumulation of milling-related alluvium could be very substantial in those places. Downward and Skinner's (*S8*) analysis of the impact of mill damming along three streams in southern England supports our proposition that widespread mill damming has altered greatly entire valley bottoms and the morphodynamics of modern streams and floodplains.

The following sampling of quotes documents the ubiquity and commonness of water mills in different parts of the world other than North America. References are given in the next section. (Note: Quote numbers are cited in Table S4.)

1. In reference to Great Britain: "On many of the sites listed in the Domesday Book, mills were still in use at the time of the Industrial Revolution of the eighteenth century, and after modernization some survived into the nineteenth and even the twentieth centuries….on a nationwide basis, each of the eleventh-century water mills may be presumed to have supplied an average of 50 households….A map of England's river system with the 5,624 Domesday water mills [see *S9*] is an amazing sight. It is literally covered with dots, especially the areas to the south of the Severn and the Trent. On rivers like the Wylye in Wiltshire the concentration of mills is remarkable: thirty mills along some 10 miles of water; three mills every mile." (*S10*, p. 12).
2. "…certain areas of Britain were, by the 1700s, beginning to experience problems with mill crowding. By 1600 or 1700, there were nine mills on 8 miles (13.6 km) of the Ecclesbourne, a small tributary of the Derwent in Derbyshire…. By the end of the 1700s there were over 100 watermills on about 20 miles (circa 35 km) of stream in the area, or five watermills for every mile (three per km) of stream." (*S7*, p. 123).
3. "The millwrights of Toulouse … build majestic dams, possibly the largest ever erected up to that time. …the city engineers…built three dams barring the fast-flowing Garonne, and erected 43 water mills on its right bank. The Chateau-Narbonnais dam drove 16 of the earthbound mills, the Daurade dam drove 15, and the Bazacle dam 12. …The Bazacle dam, first mentioned in a document of 1177, was some 400 meters (1300 feet) long and was situated diagonally across the river…it was built by ramming thousands of oak piles approximately 6 meters long into the riverbed by means of a ram or piledriver. The dam engineers thus formed a series of parallel palisades and filled the spaces between with earth, wood, gravel, and boulders to reinforce the dam and make it watertight. …Time and again through the centuries there were complaints followed by lawsuits

because the owners of the downstream dams illegally raised the height of their dams to increase their waterpower…in 1356…the Bazacle dam had been raised to such a height as to put the Daurade mills out of action.” (*S10*, p. 17-18).

4. “The example of Paris in the early fourteenth century shows how close to one another water mills were built in a medieval city. There were sixty-eight in the upstream section alone of the main branch of the Seine. This went from the rue des Barres on the right bank, on the level of the present church of Saint-Gervias, across the Grand Pont … to the eastern tip of the Ile Notre-Dame, a distance of under a mile (1450 meters).” (*S10*, p. 16-17).
5. “…France had around 80,000 watermills in 1700. These watermills, particularly the 15,000 industrial watermills and the 500 water-powered metallurgical plants, provided the French kingdom with a substantial base for industrialization. They no doubt played an important role in the revival of the French economy in the 18th century …*water-powered forges had become so numerous that dams, mill races, and reservoirs were situated one after the other, almost without break on some streams.*” [emphasis added] (*S7*, p. 123-127).
6. “As in England, the growing use of waterpower in France had produced regions where watermills were crowded quite close together…By the early modern period there were 300 watermills around Ambert in central France. Ferrendier noted that the Furan River in 1753 had more than 250 watermills in a distance of around 25 miles (40 km), including flour, saw, paper, polishing, gunpowder, and hammer mills. At Vienne, in eastern France, on 3 miles (5 km) of stream there were more than 100 water wheels, almost one every 150 feet (45 m). In Picardy, Ferrendier reported 100 watermills on the Thirain River, 51 on the Breche, 60 on the Authie, 50 on the Aa, 40 on the Escaut, 34 on the Selle, and 130 on the Bresle, all rather small streams. “Over all the territory of France,” he concluded, “there was not a river which did not drive a mill.”” (*S7*, p. 124).
7. “In Germany, too, dams, reservoirs, and power canals were in frequent use by the sixteenth and seventeenth centuries. Agricola, for example, noted in 1556 that when no stream could be diverted to the top of a vertical water wheel, Saxon miners usually collected water in large reservoirs, presumably through the use of a system of dams and canals, and then directed it by means of sluice gates against the blades of undershot water wheels.” (*S7*, p. 127-128).
8. “In the 700 years between 500 and 1200 A. D., in spite of long periods of political and economic chaos, the water wheel spread over the entire European continent. By the thirteenth century it was known and in use from Spain to Sweden, from Britain to Bulgaria, from Rome to Russia.” (*S7*, p. 51).
9. In reference to Bulgaria, Romania, and Yugoslavia, early 20th century: “Water mills were densely lined along river sides, because of the mountainous terrain of the country and the great number of rivers. The distances from the settlements to the mills and back were not big generally.” (*S11*, p. 452).
10. “Over the past two decades, a number of classical archaeologists and historians have demonstrated that Roman use of waterpower was far more widespread and innovative than was previously thought.… [and] the vertical-wheeled water mill was in widespread use throughout the Roman Empire for at least the first half of the second century C. E.…” (*S11*, p. 7).

11. "Further, Paul Aebischer, who studied the occurrence of Latin terms for "watermill" in medieval Italian documents, found that by the eighth century watermills were known in Tuscany, Latium, and Lombardy, and by the ninth in the provinces of Emilia, Piedmont-Liguria, and Compania. By the mid-tenth century they were commonplace through most of Italy." (*S7*, p. 49).
12. "There is nevertheless clear evidence that waterpower was used widely in the Chinese metallurgical industry from at least the early third century onward, while the use of watermills for grinding grains and seeds was widespread from at least the fifth century onward. Water milling was so commonplace throughout China by the tenth century that two commissioners for water mills were appointed to oversee the industry…." (*S11*, p. 9).
13. "…there is clear archaeological evidence in the Middle East for the use of water mills from as early as the seventh century. The archaeological evidence suggests that both horizontal- and vertical-wheeled water mills were in widespread use from at least the ninth century. … By the time of the Crusades, there were reputedly mills in every province of the Muslim world from Spain and North Africa to Central Asia." (*S11*, p. 10).
14. "The English colonies in North America were not unique. The transplantation of the watermill occurred with equal rapidity in other European colonies of the period. The Dutch, for example, began colonizing southern Africa in 1652. By 1659 the colony had a vertical watermill." (*S7*, p. 154).
15. "The French attempted to transplant Europe's seignorial system, including the manorial watermilling monopoly, to their colonies in Canada. French Canadian law encouraged seigneurs to construct mills by requiring those who intended to enforce banal rights to erect a mill within a year of assuming their estates. Most seigneurs met the requirement. French Canada had 44 gristmills by 1688 and 120 by 1739, most of them water-powered." (*S7*, p. 154).

Supporting figures

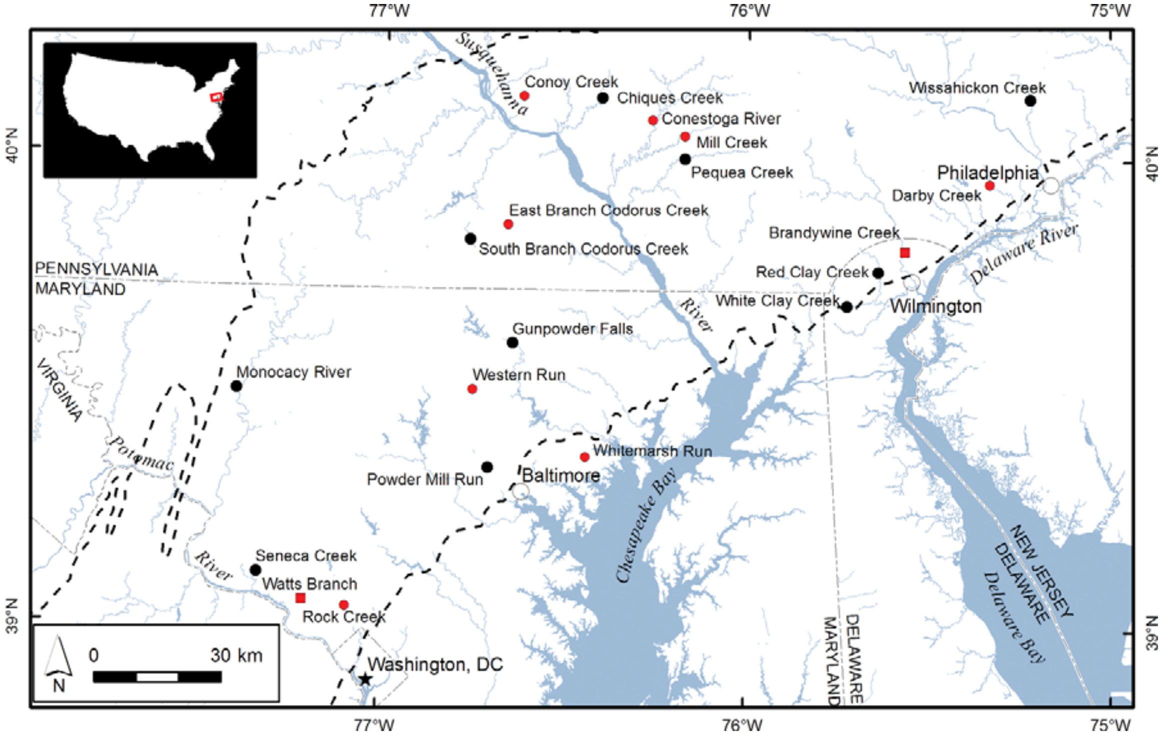

Figure S1. Watersheds (n = 20) studied in this investigation. Red circles indicate watersheds for which we have radiocarbon dates from pre-settlement organic material buried beneath post-settlement alluvium (slackwater sediment). Red squares indicate watersheds for which previous workers have obtained radiocarbon dates from pre-settlement organic material buried beneath post-settlement alluvium (slackwater sediment). All dates from our work (n = 64) are between 300 and 11,240 yrs BP (see table S3). We interpret the hydric soils as stable Holocene wetlands that were buried at the onset of European land-clearing and damming for water-powered mills. We have lidar for the Conestoga watershed, Pennsylvania, and for Baltimore County, Maryland, the latter of which includes Western Run and Whitemarsh Run. [Figure prepared by M. Rahnis.]

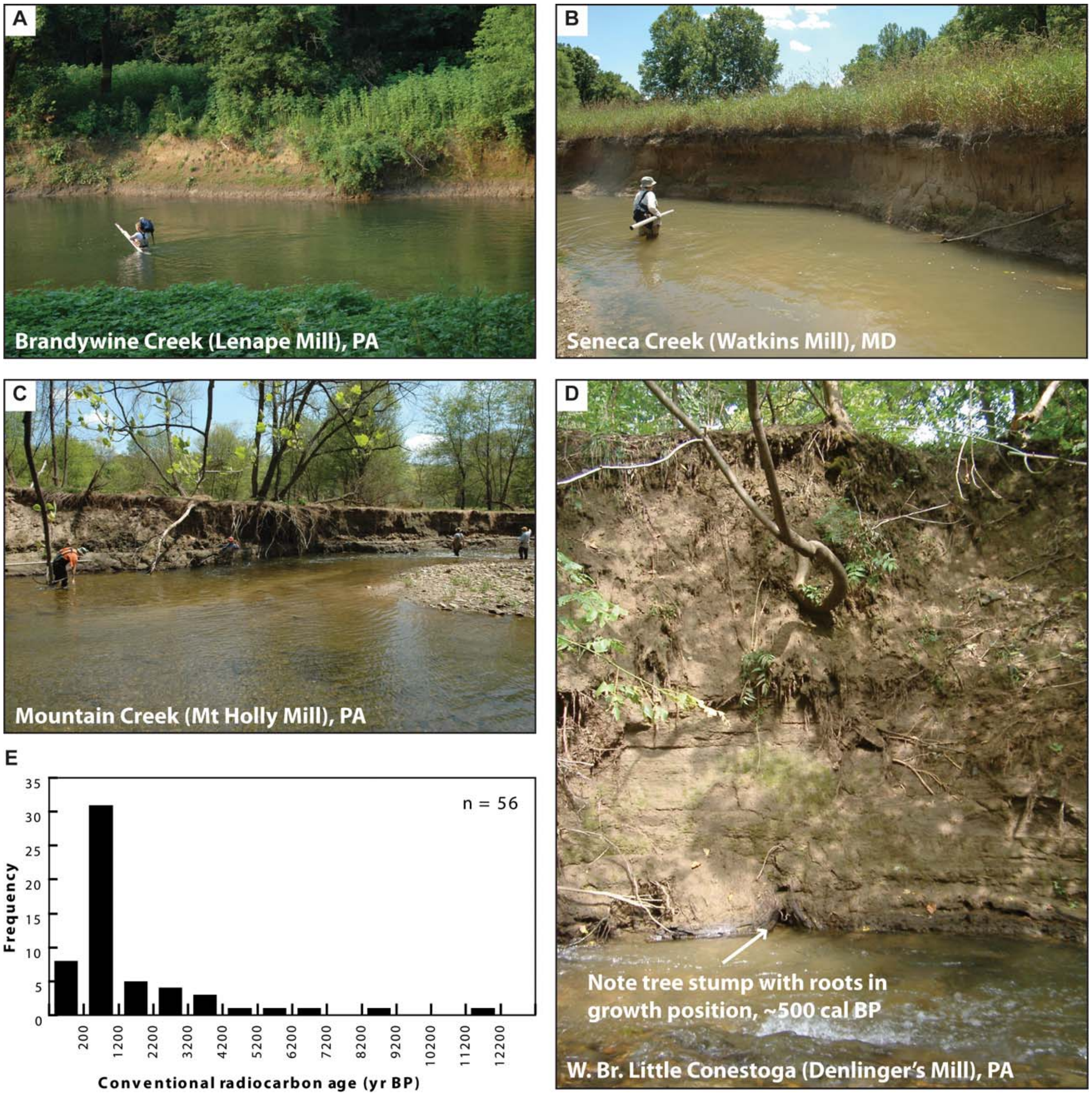

Figure S2. Eroding banks of post-settlement alluvium upstream of mill dams along (A) Brandywine River, PA, 3-m high banks (note person up to waist in water); (B) Seneca Creek, MD, 2.5-m high banks; (C) Mountain Creek, PA, 4-m high banks; and (D) Conestoga River (W. Branch Little Conestoga), PA, 5-m high banks. Streams throughout the mid-Atlantic region (see sites in fig. S1) have similar characteristics, including vertical to near-vertical banks (commonly eroding); 1 to 5 m of laminated to massive fine-grained (silt and clay) sediment overlying a dark organic-rich layer; and a basal gravel that usually is dominantly quartz and often is angular to sub-rounded. The gravel commonly is colluvium rather than alluvium, and overlies bedrock in all cases. We interpret the organic-rich material as the original valley bottom prior to European land clearing and mill damming. Analysis of the geochemistry and plant composition (primarily seeds and wood) of this material indicates open marsh to sedge marsh and shrub-scrub wetland environments (obligate to facultative-wetland). (E) Radiocarbon dates (n = 56) from the buried organic-rich hydric soils in multiple watersheds range in age from ~300 to 11,240 yrs BP, indicating that wetlands were widespread and stable throughout much of the Holocene interglacial warm period in the mid-Atlantic region.

Figure S3. Historic maps such as this township map were used to locate mill dams in central and southeastern Pennsylvania and in northern Maryland. (A) Historic mills, millponds, races, and dams in the Conestoga watershed, PA, on 1864 “Bridgen’s Atlas of Lancaster County, Pennsylvania”. Lidar for area in red box is illustrated in Fig. 4b and 4c of text. Note that our lead-210 dating of sediments indicates that millponds in this area were filled with sediment by 1850, consistent with the small size of remnant ponds shown in this 1864 map. (B) Photograph of Lancaster County mill dam (May 13, 1919) from PA DEP Dam Safety inspection files. This 2.7 m high dam is illustrated in Fig. 4 of text (see breached dam at 7 km on W. Br. Little Conestoga Creek). The modern stream is deeply incised to bedrock at this location, with actively eroding banks and exposed pre-settlement hydric soils from which a bitternut hickory nut (*Carya cordiformis*) yielded a radiocarbon age of 6940 to 7170 cal BP (Beta Analytic, Inc. laboratory results).

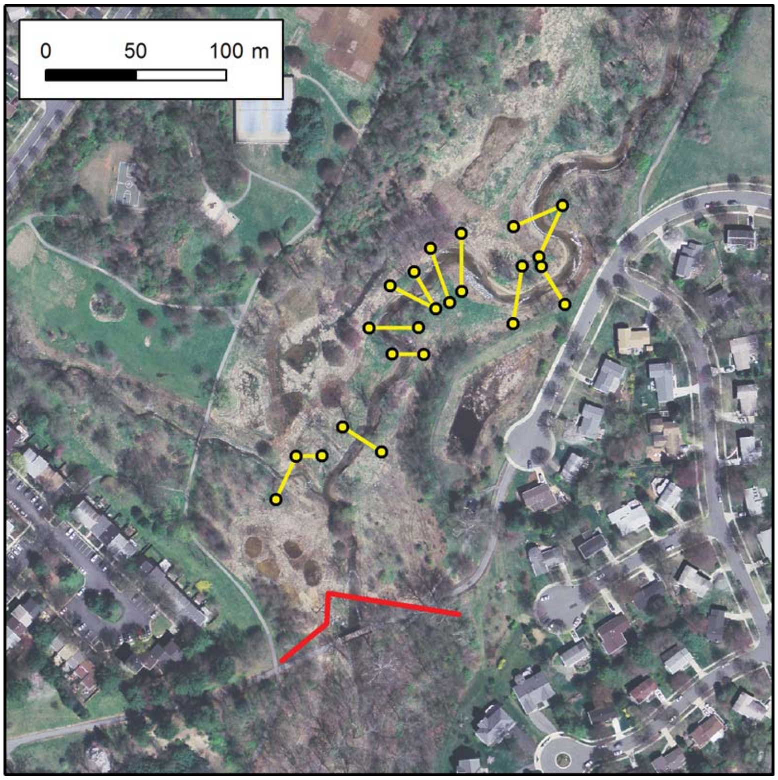

Figure S4. Here we show that stream channel erosion and migration monitored for 41 years (yellow lines with end points mark approximate locations of surveyed cross sections) in a study of meander migration and floodplain formation near the headwaters of Watts Branch, MD (*S12*, *S 13*) are located immediately upstream of a breached 19th c. mill dam (red line marks approximate location) that was not recognized by previous workers. (Flow is from top to bottom, approximately north to south, in view.) This dam supplied water to Wootton's Mill, which operated until 1905 and was located <1 km downstream of the dam (toward bottom of view). The higher valley flat surface upstream of the dam is interpreted here as a fill terrace rather than as a floodplain, even though it might now receive occasional overbank flow.

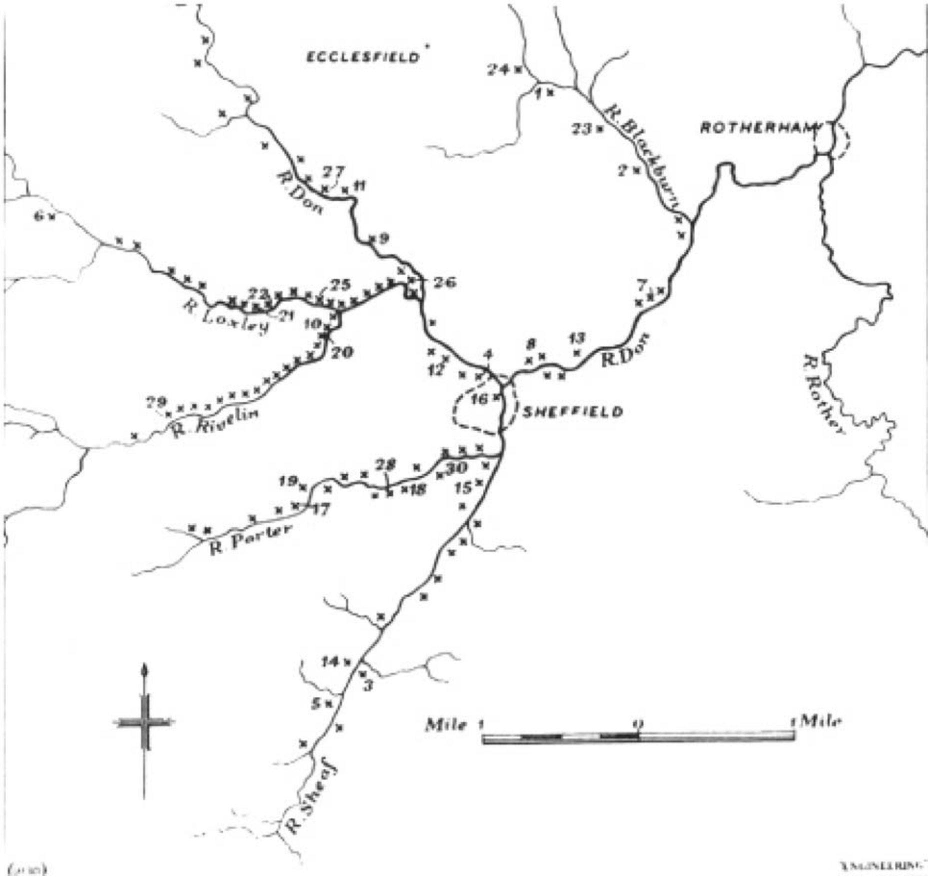

Figure S5. Distribution of watermills near Sheffield, England, 18th century, indicating mill crowding along small streams. Cross-marks indicate mill locations. (Figure from (*S7)*. Original source: Allison, Archibald, 1948, The waterwheels of Sheffield: Engineering, v. 165, p. 165-168.)

Supporting tables

Locality (Site)	State, County	N (ppm)	N Load (lbs/ton)	C (ppm)	C Load (lbs/ton)	P (ppm)	P Load (lbs/ton)	Type
Big Spring Run	PA, Lancaster	1658	3.32	15869	31.7	539	1.08	Average
Denlinger's Mill	PA, Lancaster	1089	2.18	10865	21.7	727	1.45	Average
Levan's Mill	PA, Lancaster	1368	2.74	27844	55.7	568	1.14	Average
Hammer Creek	PA, Lancaster	2162	4.32	30857	61.7	958	1.92	Aggregate
Conoy Creek (T1)	PA, Lancaster	415	0.83	5640	11.3	532	1.06	Aggregate
Conoy Creek (T2)	PA, Lancaster	533	1.07	6813	13.6	493	0.99	Aggregate
East Branch Codorus Creek	PA, York	790	1.58	10540	21.1	527	1.05	Average
East Branch Codorus Creek	PA, York	554	1.11	8691	17.4	527	1.05	Aggregate
Penns Creek	PA, Centre	1256	2.51	13398	26.8	480	0.96	Average
Penns Creek	PA, Centre	1142	2.28	12952	25.9	429	0.86	Aggregate
Emmas Creek	PA, Huntingdon	1758	3.52	23582	47.2	339	0.68	Aggregate

Table S1. Summary of measured total nitrogen (N), carbon (C), and phosphorus (P) concentrations in aggregate stream bank deposits (pre- and post-settlement strata) in the Piedmont and Ridge and Valley Physiographic Provinces of Pennsylvania. Nitrogen and carbon were measured by elemental combustion gas chromatography. Phosphorus concentrations were measured by ICP-OES using the U.S. EPA 3051 microwave digestion method. Average values represent the average of individual analyses in 10 cm increments throughout the entire stream bank vertical profile. Aggregate values reflect single measurements of pooled (aggregate) samples from throughout the vertical stream bank sediment profile. Element concentrations measured at Franklin and Marshall College in the Environmental Geochemistry lab by R. Walter, K. Mertzman, Y. Voynova, I. Weaver, and J. Weitzman.

Stratigraphy	C (wt %)	Bulk Density (kg/m^3)	Depth (m)	Tonnes carbon/hectare
Aggregate Stream Bank	1.50	1300	2.00	390
Pre-Settlement (minimum carbon)	3.00	900	0.50	135
Pre-Settlement (maximum carbon)	9.00	1500	1.00	1350
Post-Settlement (average carbon)	1.30	1300	1.50	254

Table S2. Representative carbon sink values (tonnes carbon/hectare) calculated from carbon concentration measurements for pre- and post-settlement deposits exposed in stream bank in the mid-Atlantic, United States, region. Carbon concentrations measured at Franklin and Marshall College in the Environmental Geochemistry lab by R. Walter.

Lab #	Field #	Method	State, County	Stream	Latitude (degrees)	Longitude (degrees)	Depth below surface (cm)	Material	Conv. ^{14}C age (yr BP) *	Error (± yr)
Beta 80056	1	Conv.	PA, Lancaster	Unnamed trib. to Little Conestoga Cr.	40.095	-76.330	71	bog organics	120	60
Beta 84240	2	Conv.	PA, York	Unnamed trib. to Little Conewago Cr.	39.981	-76.807	116	bog organics	480	60
Beta 56672	3	Conv.	PA, Carbon	Aquashicola Creek	40.792	-75.612	99	bog organics	3150	60
I 14002	4	Conv.	PA, York	Codorus Creek	40.013	-76.712	276	bog organics	470	60
Beta 6416	5	Conv.	PA, Lebanon	Snitz Creek	40.335	-76.463	122	bog organics	3690	80
Beta 7504	6	Conv.	PA, Lancaster	Cocalico Creek	40.175	-76.199	98	bog organics	200	60
Beta 58257	7	Conv.	PA, Berks	Schuylkill River	40.282	-75.848	207	charcoal	500	80
Beta 51311	8	Conv.	PA, Lancaster	Pequea Creek	39.934	-76.281	0	charcoal	630	70
I 16191	9	Conv.	PA, Lancaster	Stauffer Run	40.054	-76.239	32	charcoal	340	80
I 15341	10	Conv.	PA, Lancaster	Seitz Creek	40.130	-76.624	25	bog organics	620	200
I 15932	11	Conv.	PA, Lancaster	Conestoga River	40.050	-76.273	91	bog organics	460	150
I 15704	12	Conv.	PA, Lancaster	Stauffer Run	40.058	-76.251	61	bog organics	2630	90
Beta 60391	13	Conv.	PA, Lancaster	Conestoga River	40.061	-76.267	123	wood	370	60
Beta 60392	14	Conv.	PA, Lancaster	Conestoga River	40.061	-76.268	122	wood	230	70
Beta 46145	15	Conv.	PA, Lancaster	Unnamed trib. to Little Conestoga Cr.	40.063	-76.356	66	bog wood	220	80
I 15931	16	Conv.	PA, Lancaster	Landis Run	40.080	-76.271	69	bog organics	1990	130
Beta 85162	17	Conv.	PA, Lancaster	Conestoga River	39.996	-76.346	184	bog organics	380	70
Beta 87328	18	Conv.	PA, Lancaster	Conestoga River	39.996	-76.346	0	charcoal	680	60
Beta 87329	19	Conv.	PA, Lancaster	Conestoga River	39.996	-76.346	0	charcoal	150	60
Beta 77496	20	Conv.	PA, Lebanon	Swatara Creek	40.450	-76.413	38	bog organics	450	70
Beta 59327	21	Conv.	PA, Lebanon	Snitz Creek	40.287	-76.423	77	charcoal	pMC	
Beta 61638	22	Conv.	PA, Lebanon	Snitz Creek	40.287	-76.423	77	charcoal	240	80
Beta 61636	23	Conv.	PA, Lebanon	Snitz Creek	40.287	-76.423	72	charcoal	330	70
I 16192	24	Conv.	PA, Lancaster	Unnamed trib. to Mill Creek	40.005	-76.300	168	bog wood	4330	100
Beta 52250	25	Conv.	PA, Berks	Schuylkill River	40.298	-75.908	0	charcoal	1680	50
Beta 65435	26	Conv.	PA, Lancaster	Conestoga River	40.000	-76.312	0	charcoal	460	70
Beta 62910	27	Conv.	PA, Lancaster	Conestoga River	40.000	-76.312	0	charcoal	390	70
Beta 64705	28	Conv.	PA, York	Codorus Creek	39.864	-76.872	0	bog wood	400	90
Beta 64706	29	Conv.	PA, York	Codorus Creek	39.868	-76.872	262	bog wood	pMC	
Beta 72276	30	Conv.	PA, York	Codorus Creek	39.870	-76.870	110	bog organics	280	50
Beta 72277	31	Conv.	PA, York	Codorus Creek	39.870	-76.870	138	bog organics	320	70

Beta 76545	32	Conv.	PA, York	Codorus Creek	39.870	-76.870	137	bog organics	300	70
Beta 73219	33	Conv.	PA, York	Codorus Creek	39.870	-76.870	97	bog organics	400	60
Beta 50267	34	Conv.	PA, York	Susquehanna River	40.147	-76.795	108	charcoal	2520	70
Beta 65860	35	Conv.	PA, Lancaster	Mill Creek	40.094	-76.063	88	bog wood	610	100
Beta 65861	36	Conv.	PA, Lancaster	Mill Creek	40.094	-76.063	84	bog wood	320	50
I 16288	37	Conv.	PA, York	Kreutz Creek	39.966	-76.597	72	bog organics	570	80
I 16289	38	Conv.	PA, York	Kreutz Creek	39.966	-76.597	108	bog organics	540	80
Beta 47339	39	Conv.	PA, Franklin	Unnamed trib. to Conococheague Cr.	39.795	-77.797	237	bog wood	11240	210
Beta 216648	RRT1-9	AMS	MD, Montgomery	Rock Run	38.998579	-77.205278	81	bog charcoal	8900	40
Beta 216685	RRT2-1	AMS	MD, Montgomery	Rock Run	38.986799	-77.198536	150	bog wood	6680	40
Beta 216687	RRT3-1	AMS	MD, Montgomery	Rock Run	38.986388	-77.197789	191	wood	pMC	
Beta 216686	RRT2 RB4	AMS	MD, Montgomery	Rock Run	38.986556	-77.198544	150	bog charcoal	670	40
Beta 211068	BS-T2-C2	AMS	PA, Bedford	Shobers Run	39.992549	-78.513179	67	bog charcoal	420	40
Beta 211069	BS-T3-C2	AMS	PA, Bedford	Shobers Run	39.991418	-78.515977	110	bog wood	2440	40
Beta 211070	BS-T4-C1	AMS	PA, Bedford	Shobers Run	39.98738	-78.519345	95	bog charcoal	1690	40
Beta 198179	BS-1 125-90	Conv.	PA, Lancaster	Big Spring Run	39.993083	-76.262632	110	bog wood	1580	60
Beta 198180	BS-1 125-130	AMS	PA, Lancaster	Big Spring Run	39.993083	-76.262632	120	bog wood	700	40
Beta 211071	BS-T4-C2	AMS	PA, Bedford	Shobers Run	39.98738	-78.519345	74	wood	160	40
Beta 211072	DR-T1-C7	AMS	PA, Lancaster	Doe Run	40.161173	-76.383482	46	charcoal	180	40
Beta 211073	DR-T2-C2	AMS	PA, Lancaster	Doe Run	40.161463	-76.382581	65	charcoal	170	40
Beta 186303	#8	Conv.	PA, Lancaster	West Branch Little Conestoga Creek	39.974194	-76.375903	500	peat	330	60
Beta 186304	#11	Conv.	PA, Lancaster	West Branch Little Conestoga Creek	39.974194	-76.375903	520	leaf material	230	60
Beta 235102	Con-T1B-82047-a	Conv.	PA, Lancaster	Conoy Creek	40.134258	-76.618345	230	wood	3960	50
Beta 235103	Con-T1B-82407-b	AMS	PA, Lancaster	Conoy Creek	40.133121	-76.621427	250	wood knot	4140	40
Beta 235104	Con-T1C-82407-c	AMS	PA, Lancaster	Conoy Creek	40.133074	-76.62136	230	peat	1910	40
Beta 235105	EBCC-91707-a	Conv.	PA, York	East Branch Codorus Creek	39.846329	-76.653312	160	bark	2150	50
Beta 235106	WM-T2-052407-a	AMS	MD, Baltimore	Whitemarsh Run	39.3794	-76.423473	400	twig	pMC	
Beta 235108	WM-T2-052407-c	AMS	MD, Baltimore	Whitemarsh Run	39.3794	-76.423473	319	twig	pMC	
Beta 235109	WR-91407-RC1	Conv.	MD, Baltimore	Western Run	39.509742	-76.747292	250	wood	3410	40
Beta 235110	WR-91407-RC3	AMS	MD, Baltimore	Western Run	39.510835	-76.746391	240	wood	760	40
Beta 232651	EBCC-61807-RC1	AMS	PA, York	East Branch Codorus Creek	39.847727	-76.653411	200	cherry seed	190	40
Beta 232652	EBCC-61807-RC2	AMS	PA, York	East Branch Codorus Creek	39.847727	-76.653411	180	wood	190	40
Beta 232653	WBLC-10107-RC1	AMS	PA, Lancaster	West Branch Little Conestoga Creek	39.995004	-76.406039	180	nutshell	6150	40

Table S3. Radiocarbon age data.

Location	Time period	Number of watermills, dams, or waterwheels	Quote*	Reference†
Great Britain (Domesday survey)	11th century	5,624-6,500 watermills (See map below)	1	*S(7,9,14,15,16)*
Great Britain	18th century	10,000-20,000 watermills and mill crowding (See map in S3)	2	*S7, S11*
Toulouse, France	12th century	early dam building for mills	3	*S16*
Paris, France	early 14th century	dense	4	*S16*
France	17th century	80,000 watermills	5,6	*S7*
Belgium	1846	2,600 waterwheels		*S7*
Germany	16th century	dams, reservoirs, power canals (mill races) in frequent use	7	*S7*
Austrian-occupied Poland	18th century	5,243 watermills		*S7*
Ukraine (northern Dneiper watershed)	18th century	1,273 watermills		*S7*
Portugal	20th century	30,000 watermills		*S10*
Norway	19th century	20,000-30,000 watermills		*S10*
Europe	6th to 13th centuries	spread of watermill technology	8	*S7*
Bulgaria, Romania, and Yugoslavia	early 20th century	dense	9	*S10*
Italy (Rome)	2nd century	widespread	10	*S10*
Italy	10th century	commonplace	11	*S7*
China	early 3rd to 10th centuries	Widely used	12	*S10*
Middle East	7th to 9th centuries	early, widespread use	13	*S10*
Southern Africa	17th century	early mill building	14	*S7*
French Canada	17th-18th centuries	120 grist mills	15	*S7*

Table S4. Global historic data on mills and dams, with quotes and references.

* Numbers are keyed to numbered quotations in the Supporting Online Material text section entitled “Global historic data on mills and dams”.

† Numbers are keyed to supporting references and notes.

Supporting references and notes

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