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SETBACKS AND SURPRISES

Forest restoration on floodplains mantled with legacy sediments: removing sediments appears unnecessary for successful restoration

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Recent studies suggest very low survival of seedlings planted in streamside areas containing thick (>1 m) deposits of legacy alluvial sediments. We planted 2,450 seedlings representing eight species in a streamside area with thick legacy sediments and monitored them for 5 years. The overall survival of approximately 60% (range across species: approximately 38–74%) was surprisingly high and mean overall growth per seedling (approximately 3.27 m) was very good, ranging between 2.5 and 4.7 m depending on tree species. Although both seedling survival and growth exhibited significant spatial variation, none of the results supports the idea that legacy sediment thickness up to 1.5 m is an important factor with regard to success of streamside reforestation. For survival, soil depth was significant for the sediment accretion zone but not the legacy sediment zone. For growth, the response was significant and positive, with the eight species on average growing significantly better as legacy sediment increased in thickness. The results suggest that the presence of legacy sediment up to 1.5 m thick should not preclude the successful restoration of natural forest along stream channels in the eastern Piedmont of North America. Finally, the study suggests that the U.S. federal criteria for reforestation success (i.e. 222 stems per hectare after 5 years) can still be met on legacy sediment sites by increasing the planting density approximately 25% from the required minimum of 296 stems per hectare to 370.

Key words: forest restoration, legacy sediments, seedling growth and survival, streamside reforestation

Implications for Practice

- Legacy sediments are present in many floodplains but do not present a barrier to successfully restoring streamside forests in the eastern Piedmont of North America.
- Seedling survival of 60% and growth of 3.3 m in height in 5 years can be achieved on legacy sediment sites by simply providing adequate protection from herbivores and competing vegetation.

Introduction

The Piedmont area of eastern North America had been largely forested from the last glaciation 10,000 years ago until the arrival of European settlers in the late seventeenth century. Although Native Americans did some forest clearing and management, their population levels and the relative extent of their clearing were low (Williams 1989). This changed with European settlement, and by the mid-1800s almost 75% of the Piedmont had been deforested (Trefethen 1976). As European settlement and land clearing expanded in the Piedmont and elsewhere, the extensive upland soil loss (ranging from 7.6 to 30.5 cm) from clearing activity resulted in deposits of alluvial sediments blanketing existing floodplain surfaces along most, if not all, Piedmont streams (Happ et al. 1940; Happ 1945; Knox 1972; Costa 1975); these depositions are now referred to as "anthropogenic alluvium," "post-settlement alluvium," or "legacy sediments" (Macklin et al. 2014) (hereafter "legacy sediments"). These deposits and the lack of riparian tree cover have long been suspected of significantly altering the region's stream geomorphology (Zimmerman et al. 1967), ecosystem structure (Sweeney 1992, 1993), and ecosystem function (Sweeney et al. 2004).

More recently, remobilization of legacy sediments via bank erosion has been proposed as another major source of suspended sediments and nutrients in streams, contributing to stream impairment and the degradation of downstream rivers and estuaries such as Chesapeake Bay (see Walter & Merritts 2008 and Donovan et al. 2016, for reviews). Indeed, a recent assessment of the health of river systems in the eastern highlands region of the United States revealed that 50.1% of the streams and rivers studied were in poor condition and that "phosphorus, nitrogen, and streambed sediments in particular have widespread and severe impacts" (USEPA 2016).

Author contributions: BS designed, funded, and executed the project; AD collected field data, literature, and synthesized data; MDD characterized the geomorphology of the site and measured legacy sediment thickness; CLD produced statistical analyses, geospatial work, tables, and graphs; all authors contributed to the writing.

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This USEPA review further suggested that "reducing levels of these constituents will significantly improve the biological health of rivers and streams." Although deposition and storage of alluvial sediments along stream channels is a natural process (Ferdowsi et al. 2017), the reports of degradation over many decades triggered a keen and continuing interest in stream channel assessment, categorization, and restoration (Bernhardt et al. 2005). In terms of stream restoration, two broad active restoration approaches have been emphasized: (1) proactive removal of legacy sediments and intensive re-engineering of the channel (sensu Rosgen 1994, 1996) to stabilize it and reconnect it to the floodplain (see Bernhardt & Palmer 2011 for review) (hereafter the sediment removal channel re-engineering [SRCR] approach); and (2) proactive reduction of the active sources of the stressor/pollutant load (sensu EPA's Total Maximum Daily Load) in the watershed while restoring the riparian area to a more natural vegetated state (usually forest in the Piedmont; sensu Welsch 1991) (hereafter the pollution reduction reforestation [PRR] approach). The PRR approach allows the stream and its channel to re-engineer itself into a physical, chemical, and biological system in equilibrium with existing watershed conditions, while allowing the reforested floodplains and riparian zones to stabilize legacy sediments and reduce rates of bank erosion.

The SRCR approach typically involves the use of large equipment to excavate and relocate legacy sediment, along with redesign and restoration of the physical stream channel. Although faster than the PRR approach, this method is invasive in the short term, relatively expensive in cost per unit length of restored stream, and whether it is better or more successful appears relatively unclear and largely unproven (Bernhardt & Palmer 2011). Alternatively, the PRR approach of riparian forest restoration has been both successful and more benign, albeit slower, with a lower cost per unit length of restored stream. PRR also provides the advantage of long-term stabilization of river banks containing legacy floodplain sediments. Consequently, PRR has been the favored approach for much of the on-going federal and state stream and watershed restoration efforts in eastern North America (e.g. USDA CREP forest buffer program).

Another dimension was added to the debate over SRCR versus PRR stream restoration approaches when publications appeared regarding difficulties associated with using planted seedlings to reestablish a forest on stream banks containing legacy sediments. Specifically, Voli et al. (2009) and Merritts et al. (2011) reported for a riparian restoration project on Big Spring Run in the Pennsylvania Piedmont that: "A planting of approximately 3,000 riparian trees on the historic silt and clay in 2002 had a high mortality rate (>95%). A possible cause of this high mortality is the height of the plant roots above the groundwater table. Typical thickness of historic sediment above groundwater (base flow level for the incised stream) at the Big Spring Run headwaters is approximately 0.9–1.2 m." They further suggested that an important implication of their study was that "restoring the naturally occurring riparian wetlands buried beneath historic sediment, rather than restoring incised stream channels or planting riparian tree upon the elevated historic sediment surface, could be a more effective and sustainable approach to increased wetland biodiversity and improved riparian habitat and function. In addition it might reduce downstream sediment and nutrient loads." However, this seemed to wrongly imply that: (1) forest tree species of eastern North America are largely groundwater dependent and that the regional levels of precipitation are insufficient to support them; and (2) the removal of legacy sediments to reconnect a stream to its pre-European settlement floodplain surface might be a prerequisite to restoring a riparian forest and, eventually, the ecological function of the aquatic ecosystem.

In this study, our intent was to reforest a streamside setting mantled by legacy sediment, similar to Big Spring Run, and to carefully monitor the survival and growth of seedlings over several years in order to: (1) confirm that areas mantled with legacy sediments are not conducive to good survival and growth of seedlings; and (2) determine to what extent it might be possible to compensate for this outcome by increasing the seedling density at the start of the restoration process. We also wanted to design the study to rule out the possibility other factors reported to be of importance in riparian forest restoration projects were not impacting seedling survival, such as, for example, competition with non-native invasive plants and consumption by herbivores such as white-tailed deer, voles, rabbits, and mice (as reported by Sweeney et al. 2002; Sweeney & Czapka 2004; Bernhardt et al. 2005; Sweeney et al. 2007; Seavy et al. 2009).

Methods

Study Site

The study was conducted at Goodwin Preserve in Franklin Township, Pennsylvania (Fig. 1A & B), a 28-acre parcel that overlies the Glenarm Wissahickon Formation, a formation similar to oligoclase-mica schist of the Wissahickon Formation (see Franklin Township 2015; PA DCNR 2015). The majority of the site contains Codorus silt loam soils, with smaller areas (plot S10 and portions of plot S09; Fig. 1A & B), having Baile silt loam soils (USDA 2015*a*). A fourth-order reach of the Middle Branch of the White Clay Creek (WCC) bisects the study site. The 28.5 km^2 watershed upstream contains a mix of primarily agriculture and low to medium density housing.

Post-European settlement land use within the township was predominately agriculture, although several mills began operation in the 1700s and remained economically important through the 1800s (Franklin Township Historic Commission 2014). The floodplains of WCC are mantled with legacy sediments typical for the region: consisting of upland soils continually eroded after land clearance and deposited and stored as floodplain alluvium varying in thickness along the stream network (Figs. 2 & 3). Today, these floodplains are hydrologically connected to the modern stream with regular inundation. Active modern sediment aggradation occurs on these floodplain surfaces via both vertical (overbank flooding deposition) and lateral accretion (a combination of point bar building and overbank

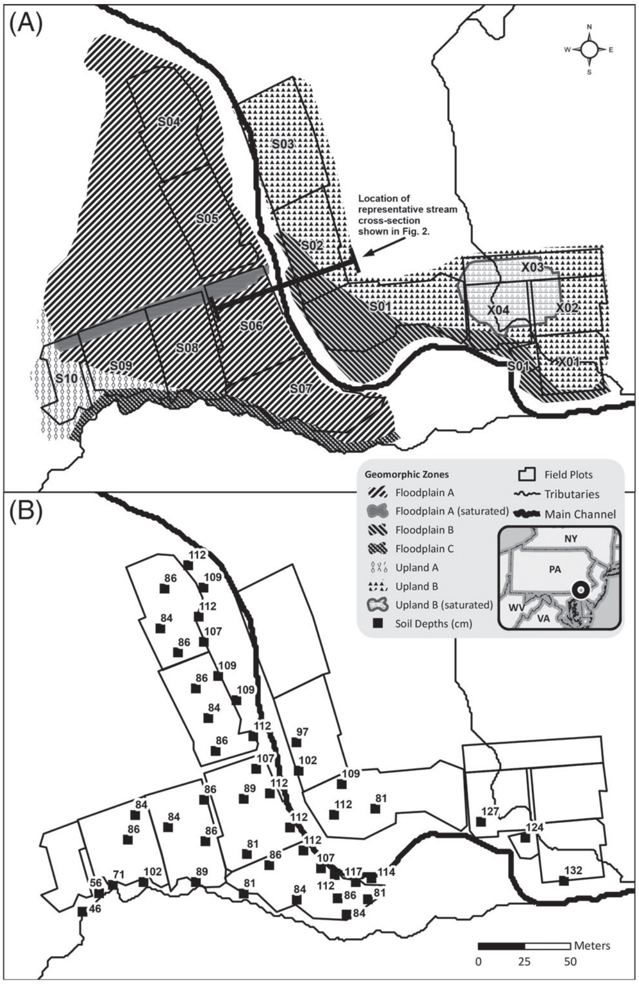

Figure 1. Showing geomorphic zones designated by soil analysis (A); soil depth (cm, A horizon) from individual cores (B), and subplots used for planting purposes (S01–S10, X01–X04; A with outlines shown in B). The saturated areas within Floodplain A and Upland B are shown merely to properly characterize the study area.

deposition as the channel migrates laterally across the valley) processes, resulting in two distinct types of floodplain geomorphic zones with different sediment characteristics. At our study site, the modern stream is actively migrating from the northeast to the southwest, eroding into the older vertical accretion floodplain zone which contains a pre-settlement floodplain soil buried under a mantle of legacy sediment deposited during overbank flooding events. As the stream erodes into this vertical accretion floodplain zone, it is actively building the lateral accretion floodplain zone to the northeast via point bar accretion and overbank deposition with modern channel-derived sediments (Fig. 2). Both floodplain zones are regularly inundated and actively storing sediment, hence meeting both hydrologic and geomorphologic definitions of floodplains (Wolman & Leopold 1957; Ritter et al. 2001). Although a dam for a paper mill was located further east and about 1.2 km downstream of the study site (Merritts 2015), it is not likely that the dam's reservoir extended far enough upstream to have contributed to the storage of legacy sediments at the Goodwin Preserve because of the differences in topographic relief.

Hydrology at the study site is best described using a 50-year record of high-frequency (5–15-minute time step) discharge measured at a site upstream of the study site along the East Branch White Clay Creek at the Stroud Water Research Center (WCC at SWRC; 1968–2014; Newbold et al. 2018). The WCC at the SWRC site (39.8586, −75.7833°; located 8.5 km from the study site) drains a 7.2 km^2 watershed having a mix of agricultural land use and forested areas. The WCC at SWRC discharge record was collapsed to a consistent 15-minute time step, by averaging the many 5-minute values to the nearest quarter hour and presenting them as cumulative flow frequency distributions (using the Cunnane plotting-position formula as per Helsel & Hirsch 2002). This was done for both the 2010–2014 study period and for the entire historic record of 1968–2018 (Fig. 4). The 5-year study period of 2010–2014 had a slightly higher overall discharge across the majority of the hydrologic regime relative to the 1968–2018 historic record. The median discharge during the study period was 0.1 m^3/s as compared to 0.09 m^3/s over the 50-year record. Bankfull discharge for the WCC at SWRC site is estimated to be 2.8 m^3/s based a location just downstream of the stream gauge having similar geomorphology to the study site (M. Daniels 2018, personal communication). The percent exceedance at this discharge varied negligibly between the two periods: 0.15 versus 0.14% for the 2010–2014 and 1968–2018 periods, respectively (Fig. 4). These percent exceedance values suggest a return period for bankfull discharge of just less than 2 years for both periods. Two significant flooding events, occurring within 2 weeks of each other, impacted the study site during the period of this analysis. Hurricane Irene produced the 17th highest peak storm discharge measured at WCC at SWRC on 28 August, 2011 followed by the eighth highest peak storm discharge measured soon after on 7 September, 2011 during Tropical Storm Lee.

Initially, for convenience, we arbitrarily subdivided the study site into 14 subplots for planting purposes. This was done knowing full well that the trees would be distributed across a variety of geomorphic landforms including upland surfaces, floodplain surfaces of varying types (including floodplain zones with legacy sediments overlying buried pre-European floodplain soils) as well as floodplain zones with only laterally accreted post-European settlement deposits. Later, in year 5, this was confirmed by careful analysis of the vertical distribution of sediments throughout the study site where we were able to distinguish seven different geomorphic zones spatially distributed across the study site (Floodplain A, Floodplain A [saturated], Floodplain B, Floodplain C, Upland A, Upland B, and Upland B [saturated]; Fig. 1A). In general, these seven zones fell spatially into three more general categories when viewed along a northeast to southwest transect across the study site and considering the type, depth, and character of sediment: Upland (including areas designated as Upland A, B, and B saturated), Recent (including areas designated as Floodplain B and C), and Legacy (including areas designated as Floodplain A and A saturated) (Fig. 1A). More specifically, these three broader categories involved hillside upland soil

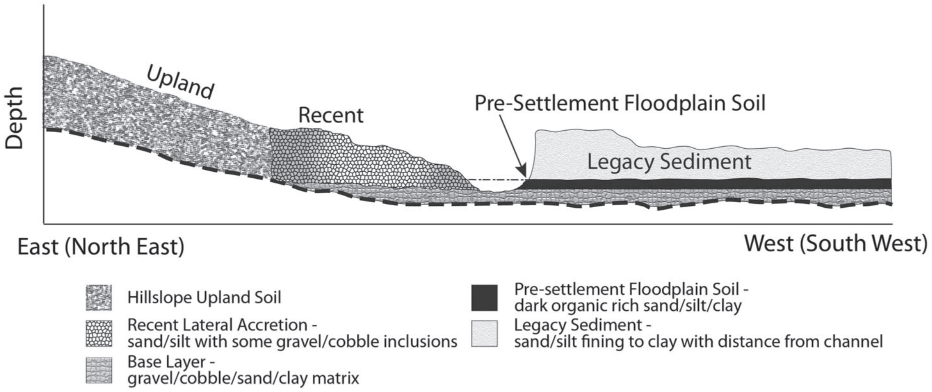

Figure 2. Representation of the upland and floodplain zones along a stream cross-section at the study site from northeast to southwest showing the Upland B, Floodplain B, and Floodplain A geomorphic zones (see text for description of these zones). See Figure 1 for assumed location of this representative cross-section.

Figure 3. (A, left) The high banks of the middle branch of White Clay Creek at Goodwin Preserve, Franklin Township, PA, represent legacy alluvial sediments. (B, right) The deposits of legacy sediments are approximately 1–1.5 m thick. Photos by Amanda Dunbar (A, left) and Melinda Daniels (B, right).

(Upland), sediment representing recent lateral accretion (of sand/silt with some gravel/cobble inclusions) over a base layer of gravel/cobble (Recent), and sand/silt/clay sediment deposited over dark (organic-rich sand/silt/clay, pre-settlement, floodplain soil; i.e. Legacy Sediment; Figs. 2 & 3).

The Goodwin Preserve, at the time of the planting, was relatively new and so public recreation use at that time was relatively low (A. Dunbar 2014, personal communication). Our study benefited from the fact that public use was infrequent and a lack of forest cover provided similar conditions for the study plots on both sides of WCC for the first 5 years of the study (Fig. 1A & B). Other than a few mature individuals of *Acer negundo* L. (boxelder), *Platanus occidentalis* L. (American sycamore), and *Juglans nigra* L. (black walnut) along its banks, prior to restoration the fields on either side of the main stream were open areas kept deforested by mowing twice a year. Mowing continued between the rows of seedlings once a year during the first 5 years of restoration (J. Auerbach, personal communication, 2015).

Seedling Planting

In 2010, community volunteers planted 2,450 seedlings (15–45 cm tall) of eight native species at the site. The planting density was 990 seedlings per hectare; this is more than 3 times the recommended planting density of the U.S. Department of Agriculture's Conservation Reserve Enhancement Program for restoring a riparian forest (USDA 2009). However, it seemed prudent because: (1) we anticipated approximately 95% mortality due to the presence of substantial areas containing legacy sediments (sensu Voli et al. 2009, Merritts et al. 2011); and (2) the landowner of the site (London Britain Township) wanted us to increase the probability that their newly created park would in fact be forested at the end of the project. We placed Tubex tree shelters (10–15 cm diameter; 1.5 m tall) over all seedlings to protect from herbivory and deer rub. The shelters were designed to eventually split, degrade, and fall off a tree as its diameter exceeded that of the shelter (Sweeney et al. 2002). Each seedling was planted at a designated location, with spacing between seedlings of approximately 3 m. The plantation extended a minimum of approximately 30 m outward on both sides of the stream. We selected a 30 m width based on Fischer and Fischenich (2000) who showed this width to provide water-quality protection, riparian habitat, flood attenuation, stream stabilization, and detrital input. This is also consistent with the currently recommended 30 m width for riparian forest buffers associated with an extensive literature

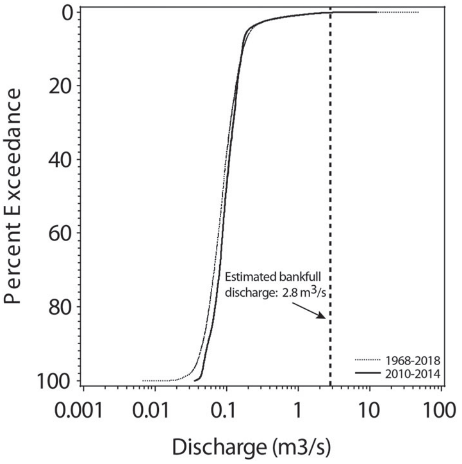

Figure 4. Cumulative flow frequency for 15-minute discharge data measured at the East Br. White Clay Creek at the Stroud Water Research Center. Two percent exceedance curves are presented; one for the entire period of record from 1968 through 2018 and one for the 2010–2014 study period. The vertical, dashed line represents bankfull discharge at a site just downstream and along the same reach as the stream gauge for the data presented here. The bankfull discharge site shares a similar geomorphic stream channel profile with the study site.

review by Sweeney and Newbold (2014). The species planted were *Acer rubrum* L. (red maple), *Acer saccharinum* L. (silver maple), *Fraxinus pennsylvanica* (green ash), *Liriodendron tulipifera* L. (tulip poplar), *Nyssa sylvatica* Marshall (black gum), *Platanus occidentalis* L. (American sycamore), *Quercus bicolor* Willd. (swamp white oak), and *Quercus palustris* Münchh. (pin oak). Species were selected because they are native to the region, reestablish well in eroded areas, have rapid growth, and/or exhibit tolerance to wet conditions (Conner et al. 2000; Sweeney et al. 2002; USDA 2015*b*).

Planting took place on two successive days. On the first day, 500 seedlings were planted in subplots X01–X04 (Fig. 1A). For these plots, the exact location and identification of each seedling were known and the height of all seedlings was measured immediately after planting. These plots were also planted with an equal number of seedlings per species ($n = 25$ for each). On the second day, the remaining 1,950 seedlings were planted across 10 other subplots (S01–S10). These planting areas were flagged at 3 × 3–m intervals throughout to indicate where seedlings should be planted. Coordinators instructed volunteers to plant the various seedling species at random throughout the 10 designated areas in an effort to avoid clusters of the same species. The exact location of each seedling and its identification was not known for plots S01 through S10 until the year 5 assessment. The seedlings were between 30 and 60 cm tall at planting (as per our individual measurements on subplots X01–X04) but the exact height of each seedling in each location for subplots S01–S10 was not recorded. For this reason, the actual height of each seedling in year 5 was used as a surrogate to estimate overall growth. All living trees in all study plots were measured at the end of the fifth growing season. Height was measured as the distance from the ground to the terminal growth bud of the living stem. Trees were considered alive if there was at least some portion of the tree visibly alive. Each surviving tree was identified and its geographic location noted on schematic maps specific to each field plot for analysis of survival and growth by location and species.

Individual seedling location was obtained by digitizing field plot schematics for all subplots. This provided the relative position of each seedling at the time of data collection in year 5 of the study. The digitized field plot schematics were then imported into ArcMap (ArcGIS Desktop v. 10.4, ESRI, Redlands, CA, U.S.A.) and geo-referenced based on previously located field plot boundaries using a handheld GPS unit to locate plot corners. Individual points representing seedling position were then manually adjusted to conform to relative position within the plots, stream reach and neighboring features (i.e. existing trees, roads, and other structures visible on aerial imagery) while also attempting to maintain the 3 m distance between stems at the time of planting. Attribute information for each seedling on the field plot schematics (including species name and survival) were entered into the attribute table for the seedling position spatial layer.

Legacy Sediment Thickness

To measure the thickness of the legacy sediment deposits at the site, we used a hand auger to core a series of locations throughout the tree planting areas within the floodplain zones (Fig. 1B). Core sites were located both on the natural levee adjacent to WCC as well as more laterally distant from the modern stream channel. Each core location was augered in 20 cm increments. Depth was measured until core extractions revealed contact with either: (1) a dark black/brown organic rich buried soil representing the pre-colonial floodplain surface; (2) a light gray clay or clay/clast mix representing the pre-Holocene periglacial upland surface; or (3) auger refusal by coarse clasts, representing previous channel bed materials now mantled by floodplain accretion.

The locations of the 47 soil cores (Fig. 1B), where legacy sediment depth was measured, were used as input to a spatial interpolation routine to estimate legacy sediment depth for the seedlings planted within floodplain zones. The spatial interpolation in the ArcGIS software requires raster data layers rather than vector leading to a number of conversions from vector (location points) to raster and back to vector to associate the interpolated soil depth data with every seedling location. The interpolation method that we used (i.e. kriging) is part of the "Spatial Analyst" set of tools within the ArcToolbox. This is a collection of geospatial tools used to create, manipulate, and analyze spatial data within ArcMap. Note that all defaults of the kriging tool were used in running the interpolation. As a final screening, any seedling located more than 61 cm (i.e. the horizontal resolution of the interpolated legacy-sediment-depth raster) from the interpolated spatial layer boundary was not included in any analyses involving soil depth. This arbitrary, though restrictive, data screening only excluded approximately 3% (39 of 1,395) of the trees planted in the two floodplain zones that were the focus of the legacy sediment sampling effort (Floodplain A and B). Excluding these trees from analyses ensured that relationships between planted trees and legacy sediment depth were confined to the spatial extent of the original soil sampling effort.

Data Analysis

As noted earlier, the eight tree species planted in the study area were not planted in equal numbers across the geomorphic zones. To provide context for the survival and height analyses, logistic regression was used to assess whether species composition, as the number of individuals present for each of the eight species planted, differed across the four principal planting areas (Upland A, Upland B, Floodplain A, and Floodplain B) at the end of the 5-year study period. The relationships between seedling survival, floodplain soil depth, and floodplain zone were examined using the following logistic regression models: (1) survival versus soil depth, floodplain (A versus B), and the interaction of soil depth and floodplain; (2) individual models of survival versus soil depth within the separate floodplains; and (3) survival versus landform (floodplain and upland areas).

Similar to survival analyses, an analysis of covariance (ANCOVA) model was used to examine growth (height) versus floodplain soil depth, landform (Floodplains A and B) and the interaction of soil depth with landform. Individual linear regression models were then performed to examine the relationship between seedling height and soil depth within the separate floodplains. Analysis of variance (ANOVA) was used to examine differences in seedling height across all geomorphic zones and across the eight planted species. Differences in height between species and geomorphic zone were analyzed simultaneously using a two-factor ANOVA with species and geomorphic zone as the factors and including an interaction between the two factors. Due to large differences in seedling numbers between species across the various zones, this analysis was confined only to seedlings planted in the Floodplain A and Upland B areas.

Height data were log10-transformed for all analyses. Non-parametric analyses, using ranked height data in place of the log10-transformed values in the same ANCOVA and ANOVA models described above were run to assess the impact of potential non-normality\outliers on the analyses. For all ANCOVA models and two-factor ANOVA models, the type III sums-of-squares (SS) results are presented rather than the type I SS. The type III SS for an independent variable takes into account variability from the other factors included in the model where type I SS do not. If there is no impact from the other factors, then type I SS will equal type III SS.

Note that some seedlings were planted within subplots that were extremely wet (e.g. often standing water in subplots X01–X04). Thus, including seedlings that were in these conditions could potentially confound the analyses that are presented here. To that end, as noted where appropriate below, analyses that involved seedlings found in extremely wet areas were re-run with those seedlings removed to assess whether inclusion of those areas had any impact on the results. Note also that unless otherwise stated, $p = 0.05$ was used as the cut-off for statistical significance throughout the manuscript.

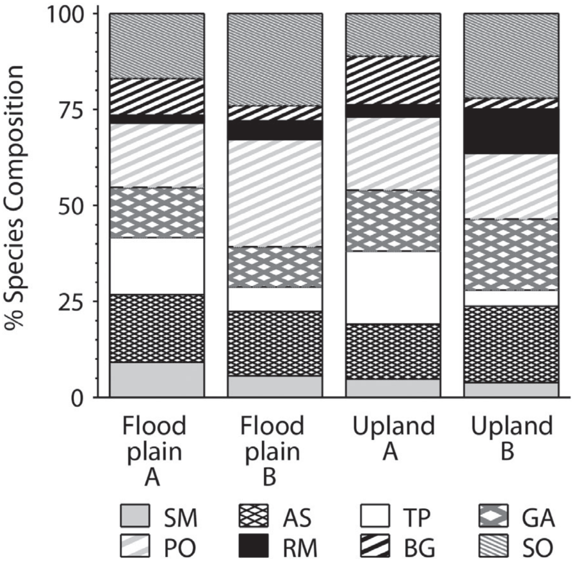

Figure 5. Species composition of surviving seedlings within the four geomorphic zones. No statistically significant differences were found in % composition among the four zones. See Table 1 for species names corresponding to abbreviations shown in the legend.

Results

Species Distribution Across Planting Zones

Given the differences in area per planting zone, most of the seedlings were planted in either Floodplain A (49% of total, 85% of the floodplain total) or Upland B (38% of total planted; 90% of upland total). Thus, a majority of the seedlings (57%) were planted within the two floodplain zones (A and B) which are critical to evaluating the central questions of this study regarding legacy sediments (Table 2, Fig. 1A). Despite the differences in numbers of seedlings planted per zone, the distribution of the seedlings by species was not found to be significantly different between the four main geomorphic zones (Wald chi-square = 3.90; $p = 0.27$; Fig. 5). Indeed, the distribution of most species surviving after 5 years mirrored the species distribution at the time of planting, with only blackgum deviating approximately 4% between planting and the year 5 inventory (i.e. 10.2% at planting vs. 6.5% survival at year 5).

Seedling Survival

Of the 2,450 total seedlings planted in the study area, 2,425 were included in assessing survival (Table 1); the excluded seedlings (as noted above) were located along the southern edge of the study site in the area designated as Floodplain C. This floodplain is for a small tributary to the Middle Branch White Clay Creek running through the study area and not exclusively influenced by the flow patterns of the Middle Branch. Overall, seedling

Table 1. Summary of seedlings planted by species and measured after 5 years. Percentages for planted seedlings are relative to the total for each individual species. Measured percentages are relative to total number of seedlings measured after 5 years. Note that of the 2,450 initially planted, 2,425 were included in assessing survival.

Species	*Nos of Seedlings Initially Planted*	*Nos of Seedlings Measured in Year 5*	*% of Planted Seedlings by Species*	*% of Total Seedlings Planted*	*% of Total Seedlings Measured*
Am. sycamore (AS)	400	267	67	16.3	18.3
Black gum (BG)	250	95	38	10.2	6.5
Green ash (GA)	300	221	74	12.2	15.2
Pin oak (PO)	450	262	58	18.4	18.0
Red maple (RO)	150	90	60	6.1	6.2
Silver maple (SM)	150	95	63	6.1	6.5
Swamp oak (SO)	450	282	63	18.4	19.3
Tulip poplar (TP)	300	146	49	12.2	10.0
Total	2,450	1,458			

Table 2. Summary statistics for survival (%) and height (cm) for planted seedlings. For the two floodplain summaries, the second value inside the parentheses indicates the number of seedlings used in analyses involving soil depth (n_{Depth}). Mean and SD values are based on all planted seedlings within a geomorphic zone.

	Floodplain A	*Floodplain B*	*Upland A*	*Upland B*
Species	*% Survival* (n, n_{Depth})			
All spp	57 (1,183; 1,154)	59 (212; 202)	64 (99)	63 (931)
	Mean height ± SD (*n*, n_{Depth})			
All spp	347 ± 117 (680; 657)	333 ± 118 (125; 117)	333 ± 134 (63)	302 ± 92 (590)
Am. sycamore (AS)	446 ± 101 (120; 118)	483 ± 112 (21; 20)	506 ± 116 (9)	389 ± 98 (117)
Black gum (BG)	258 ± 50 (65; 64)	277 ± 47 (5; 5)	253 ± 38 (8)	242 ± 50 (17)
Green ash (GA)	305 ± 74 (89; 88)	283 ± 68 (13; 12)	341 ± 78 (10)	311 ± 64 (109)
Pin oak (PO)	309 ± 78 (114; 108)	298 ± 84 (35; 31)	240 ± 63 (12)	277 ± 69 (101)
Red maple (RO)	310 ± 104 (14; 12)	230 ± 21 (6; 5)	210 ± 21 (2)	254 ± 55 (68)
Silver maple (SM)	490 ± 123 (62; 59)	462 ± 152 (7; 7)	468 ± 140 (3)	422 ± 92 (23)
Swamp oak (SO)	266 ± 65 (115; 112)	275 ± 58 (30; 29)	227 ± 48 (7)	241 ± 52 (130)
Tulip poplar (TP)	375 ± 105 (101; 96)	397 ± 95 (8; 8)	393 ± 141 (12)	327 ± 87 (25)

survival was 60% and ranged from a low of 38% for blackgum to a high of 74% for green ash (Table 1).

Survival was significantly related to soil depth, floodplain zone, and the interaction of depth with floodplain zone based on a two-factor, logistic regression analysis involving only the floodplain areas (overall Wald chi-square = 19.3, $p < 0.0002$). The subsequent survival analyses by floodplain zone showed that survival was significantly, and positively, related to soil depth in the lateral accretion floodplain (Floodplain B; Wald chi-square = 17.3, $p < 0.0001$; Fig. 6B), but not significantly related to soil depth in the legacy sediment floodplain (Floodplain A; Wald chi-square = 2.04, $p = 0.15$; Fig. 6A).

Seedling survival showed a gradual increase across the four geomorphic zones (Wald chi-square = 8.16; $p = 0.043$; Fig. S1), with survival being greatest in Upland B and gradually declining in Upland A then Floodplain B and then Floodplain A. The statistical difference in survival across these zones was between Floodplain A and Upland B. The odds ratio estimate defining the difference between these two geomorphic zones was 0.78. This value suggests that survival of the seedlings planted in Floodplain A was about 78% that of seedling survival in the Upland B, when no other factors (such as a-horizon soil depth) were taken into account. Eliminating the 250 seedlings located within the extremely wet areas (i.e. sites X0–X4 within Upland B) altered the results by not showing significant differences between any of the geomorphic zones.

Seedling Growth

Overall mean seedling height (growth) after 5 years was 3.3 m and ranged from 2.5 to 4.7 m depending on the species. ANCOVA showed that seedling height was significantly related to floodplain zone (type III MSE = 0.11; $p = 0.03$; see also Fig. S2) and the interaction of floodplain zone and soil depth (type III MSE = 0.16; $p = 0.008$; see also Fig. 7A & B), but not with soil depth as an individual factor (type III MSE = 0.06; $p = 0.10$). We obtained the same results when we performed the ANCOVA using ranked data as well as when we reran the ANCOVA after removing seedlings located in the extremely wet areas. The significant interaction of floodplain zone and soil depth was corroborated by individual linear regressions of seedling height versus soil depth for each floodplain (Fig. 7A & B). Thus, seedling height was significantly, and positively, related to soil depth in Floodplain A (type III MSE = 0.46; $p = <0.0001$) but not in Floodplain B (type III MSE = 0.01; $p = 0.58$).

ANOVA also showed significant differences in seedling height between the four geomorphic zones (ANOVA type III

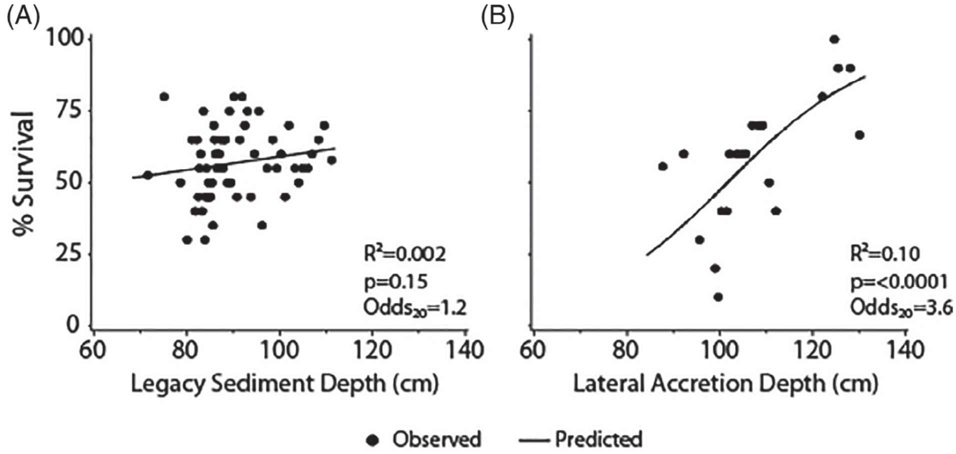

Figure 6. Seedling survival versus soil depth within the legacy sediment (A) and lateral accretion (B) floodplains. Predicted relationships based on a logistic regression of % survival versus soil depth. Relationship strength given as the r^2 value; significance of a relationship, based on the Wald chi-square test, provided by the p value; the direction of a relationship is based on the odds of survival increasing with a 20 cm increase in soil depth (Odds_{20} value). Observed % survival as presented was based on binning the data into groups of 10 consecutive observations, based on soil depth, and then calculating a % survival value for each group. This binning of survival data was done solely for plotting purposes.

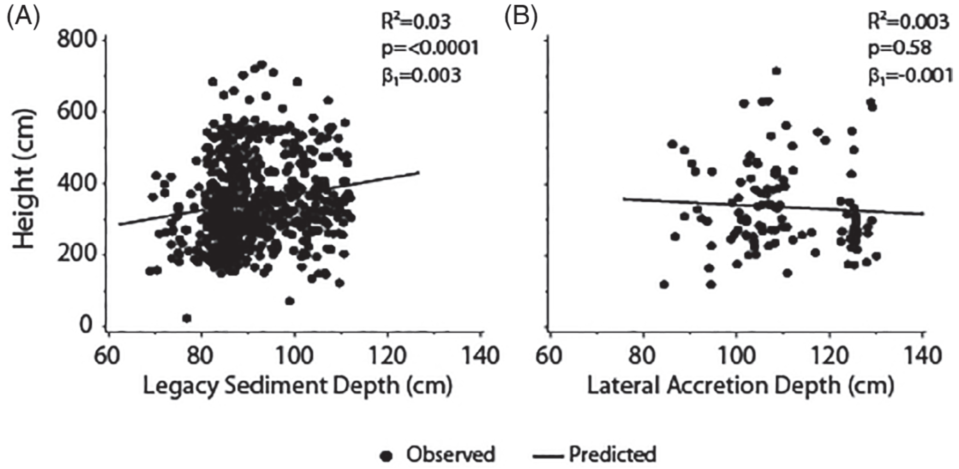

Figure 7. Seedling height versus soil depth within the legacy sediment (A) and lateral accretion (B) floodplains. Predicted relationships based on linear regression. Relationship strength given as the r^2 value; significance of a relationship, based on the overall model F-value, provided by the p-value; the direction of a relationship is based on the regression slope (β_1). Note also that ANCOVA showed seedling height to be significantly related to floodplain zone ($p = 0.03$).

MSE = 0.33; $p < 0.0001$) (Fig. S2). The ranked-data ANOVA and the initial ANOVA performed after removing seedlings from the extremely wet areas only showed significant differences between Floodplain A and Upland B. Seedling height also varied significantly among the eight species (ANOVA type III MSE = 1.69; $p < 0.0001$) (Fig. S3). The primary result was that mean heights for silver maple and American sycamore were greater than and significantly different from the remaining six species, followed by tulip poplar, which had the next tallest mean height and was likewise significantly different from the remaining six species. The results for the three tallest species were consistent regardless of whether seedlings from the extremely wet sites were removed. There were minor differences among the remaining species (in terms of significance differences), but no major re-ordering or re-grouping of those seedling species. The two-factor ANOVA relating seedling height to geomorphic zone (Floodplain A and Upland B, only) and species did provide a significant interaction term (type III MSE = 0.03; $p = 0.048$), suggesting a difference in the mean heights among the species within the two geomorphic zones.

Discussion

Seedling Survival and Growth

Our study shows that overall seedling survival across the four planting zones was 60%, far better than the expected approximately 5% previously reported on other legacy sediment sites (Voli et al. 2009; Merritts et al. 2011). It also shows that overall seedling survival was not spatially homogeneous, but rather varied somewhat across four geomorphic zones, with survival being greatest in the Upland B zone (approximately 63%) and gradually declining in Upland A then Floodplain B to a low of approximately 57% for Floodplain A. Moreover, the observed differences in survival between Floodplain A and Upland B were also statistically significant. Differences across floodplain zones were indicated by a statistically significant interaction term in the analysis regarding seedling survival, floodplain location, and depth of soil. Further analysis showed that survival was significantly and positively related to soil depth in the lateral accretion floodplain (Floodplain B) but not significantly related to soil depth in the legacy sediment floodplain (Floodplain A). In addition, the positive relationship between soil depth and survival for Floodplain B suggested that with every 20 cm increase in depth of soil deposited in the lateral accretion zone, survival increased nearly four-fold (odds ratio estimate = 3.6). One possible explanation for these patterns is that laterally accreting floodplain sediments (e.g. Floodplain B) represent the most recently formed area of floodplain near the active channel. Thus, these thinner sediments are also at a lower elevation and so the seedlings are prone to more frequent inundation and flood debris damage; these factors may be underlying the significant positive relationship between sediment depth and seedling survival within the laterally accreting floodplain zone. In contrast, we do not think that the observed pattern is being affected by the unusually wet conditions found within limited portions of the study site (e.g. X0–X04 sites) because the results remained the same even when we removed seedlings that were planted in those extremely wet areas. So, for seedling survival, the depth of the lateral accretion sediments, as opposed to legacy sediment depth, appears to be the key factor underlying spatial variation in survival across the study site floodplains.

It is difficult to put the above levels of seedling survival into perspective because, as with most riparian plantings, survival varies species by species and with regional and site conditions. Additionally, yet equally important, few studies followed survival of individual trees and species over time. However, based on our previous reforestation efforts in the Piedmont and Coastal Plain using methods very similar to this study (i.e. planting densities, potted seedlings, shelters, etc.), the overall level of survival of 60% after 5 years in this study seems very good. This survival rate falls within the range of published values from the previous reforestation studies (namely, 49% after 4 years, 70% after 3 years, and 82% after 5 years reported by Sweeney et al. 2002, Sweeney et al. 2007, and Sweeney & Czapka 2004, respectively). Perhaps more convincingly, Pannill et al.'s (2001) review of 130 randomly selected riparian restoration sites in Maryland involving planted trees showed that the average survival success was identical to that of this study (i.e. 60%).

It is also worth noting that there was no indication that survival of any of the tree species tested were more or less vulnerable to the range of conditions across the site. Perhaps this was due to the fact that the species chosen for this riparian study were all appropriately chosen to be compatible with wet soils and overall wet conditions. Regardless, they were also chosen to provide insights into whether the presence of legacy sediments might stress trees by disconnecting them from sources of hydration from deeper groundwater or provide an unstable base for supporting the trees as they grew vertically. Thus, the species (oaks, maples, sycamore, tulip poplar, etc.) included in the study represented a fairly broad array of trees with regard to probable rooting depth across a range of soil conditions (as per Crow 2005) and we expected, a priori, to observe differential mortality among species across the four geomorphic planting zones. However, in fact, the distribution of species surviving after 5 years was not significantly different from the time of planting across the four geomorphic zones, even though the majority of the plants and species were planted across highly contrasting geomorphic zones (Floodplain A vs. Upland B).

In contrast to the observed lack of pattern regarding species to species differences in survival across our study site, seedling growth (i.e. as based on height after 5 years) did vary significantly across our eight study species (using ANOVA). This was driven primarily by the fact that mean heights for silver maple and American sycamore were significantly greater than for the remaining six species. This was not surprising because silver maple and American sycamore are generally considered to be among the fastest growing trees in eastern North America (Rothenberger 1988). These results were generally unaffected by inclusion or noninclusion of seedlings from the extremely wet areas.

In addition to differences in seedling growth among species, there was also clear indication (using ANOVA) that significant variation in overall seedling growth occurred across the geomorphic zones of the study site. Significant differences in growth were observed using ANOVA between Floodplain A and Upland B, with average height greater in Floodplain A versus Upland B. This result for growth is somewhat in contrast to seedling survival where Upland B survival was significantly greater relative to survival in Floodplain A. Perhaps the most unexpected finding was that seedling growth was significantly, and positively, related to soil depth in the legacy sediment zone (Floodplain A). This was not anticipated because, as noted earlier, a previous study had reported 95% mortality for seedlings in planting zones containing similar thicknesses of legacy sediments (Voli et al. 2009; Merritts et al. 2011).

In terms of the relative magnitude of growth, mean seedling height after 5 years when averaged across all species was 3.3 m. Again, it is difficult to put this into perspective because growth varies from species to species as well as with regional and site conditions, and few studies have followed growth of individual trees over time. However, Sweeney and Czapka (2004) reported 5-year growth for two of the species included in this study, red maple and pin oak, to be approximately 1.3 and 1.6 m, respectively, for a coastal plain site near the Chester River, Chestertown, MD. Additionally, Sweeney et al. (2002) reported 4-year growth to be approximately 0.7 and 0.8 m for red maple and pin oak, respectively, on another restoration site on the Chester River. Both published studies started with similar-sized seedlings and had similar planting densities and shelter protection as in this study; therefore, we propose that the 2.6 and 2.9 m growth for red maple and pin oak, respectively, as well as the average growth of 2.5–4.7 m across all species reported after 5 years for this study was very good.

We explored whether the overall level of growth (3.3 m) and survival (60%) would satisfy the minimum federal criteria for streamside reforestation. It turns out that there are no criteria for growth, but there are criteria for survival. For example, 75% survival after 5 years is needed for a reforestation project funded by the USDA CREP program to be considered a success. This federal goal is based on a required minimum planting density of 296 stems per hectare and at least 222 stems per hectare surviving after 5 years. As noted earlier, our initial planting density was substantially higher than that (990 seedlings per hectare) because as noted earlier: (1) we expected a priori a very high mortality level because such a high proportion of the study site is mantled by legacy sediment (49% as Floodplain A); and (2) the landowners needed some assurance that the site would be reforested at project end. In hindsight, given the observed 60% level of survival, we could have reduced our starting density by 62% (from 990 to 370 stems per hectare) and still achieved the 222 stems per hectare required for a successful USDA CREP project.

In this study, seedling survival and growth both exhibited significant responses to soil depth across the study site or at least some depth-related variable (e.g. nutrients). However, neither the growth or the survival data support the idea that legacy sediment thickness should be a factor of concern with regard to reforestation success because: (1) for survival, depth of legacy sediment was nonsignificant for the legacy sediment zone and only a factor for the sediment accretion area; (2) for growth, the relationship with legacy sediment thickness was significant but positive (i.e. the eight species of trees on average grew significantly better as legacy sediment increased in thickness); and (3) the magnitude of seedling growth after several years appeared to be very good relative to past field studies of some of the same species.

These results suggest that the presence of legacy sediment up to 1.5 m thick (i.e. the level associated with this study) does not appear to be a factor that can or should preclude the restoration of natural forest along stream channels in the eastern Piedmont of North America. Our data show that in only 5 years, the riparian area of our study site was well on its way to a more natural vegetated state (i.e. forest). Additionally, other studies have shown that, once repositioned in a forest setting, the channel would eventually re-engineer itself into a physical, chemical, and biological state of equilibrium (sensu Zimmerman et al. 1967, Sweeney et al. 2004). Thus, we conclude that, although further study is needed on sites with uncommonly thick legacy sediments (i.e. >1.5 m), our data support the notion that riparian legacy sediments up to 1.5 m in thickness do not need to be removed as a prerequisite to reforestation or as a first step in the process of restoring the ecological function of stream ecosystems.

Implications for Stream Restoration in the Presence of Legacy Sediments

This study suggests that the presence of legacy sediments up to 1.5 m thick does not negatively affect seedling growth or survivorship or preclude the restoration of natural forest along stream channels. The study fails to support the proactive removal of the legacy sediments and intensive re-engineering of the channel (i.e. the SRCR approach) as a necessary pre-requisite for reforesting streams containing reasonable levels of legacy sediments. It is suggested that increasing the minimum initial planting density (296 stems/ha) of USDA CREP forest restoration projects by about 25% would be sufficient to assure success (i.e. 222 stems/ha after 5 years) for areas along streams and rivers with banks mantled by legacy sediments in the eastern Piedmont of North America.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. Percent survival of seedlings within each of the four geomorphic zones based on logistic regression analysis (see text for details).
Figure S2. Means and related summary statistics for seedling height within each of the four geomorphic zones.
Figure S3. Mean (shaded circle), median (horizontal bar), and 75th and 25th percentile (upper and lower end of box, respectively) of the medial for seedling height by seedling species across the four geomorphic zones.

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Supplemental Figures and Figure Legends Sweeney et al ms (ID REC-19-062)

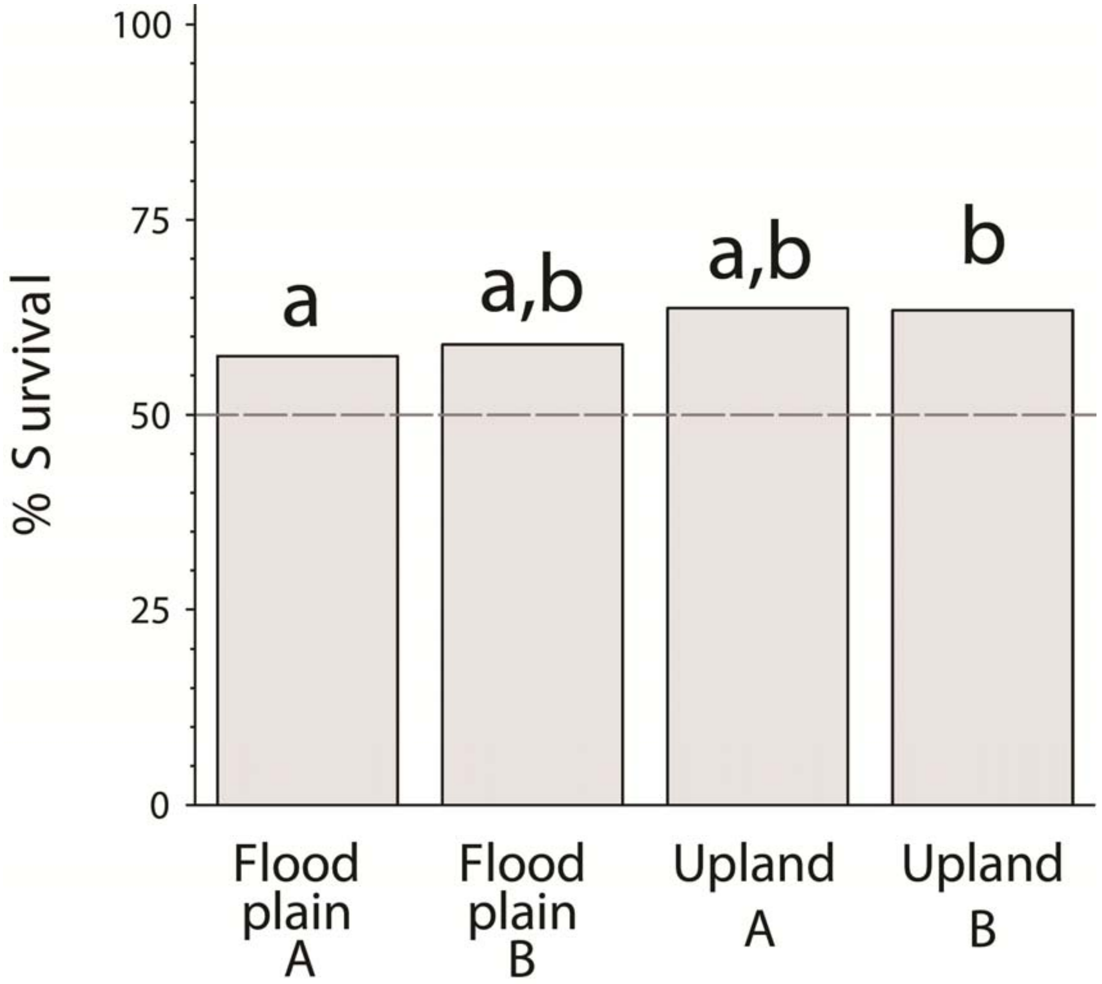

Figure S1. Percent survival of seedlings within each of the four geomorphic zones based on logistic regression analysis (see text for details). Significant differences in seedling survival between land forms indicated by differing letters on top of the bars.

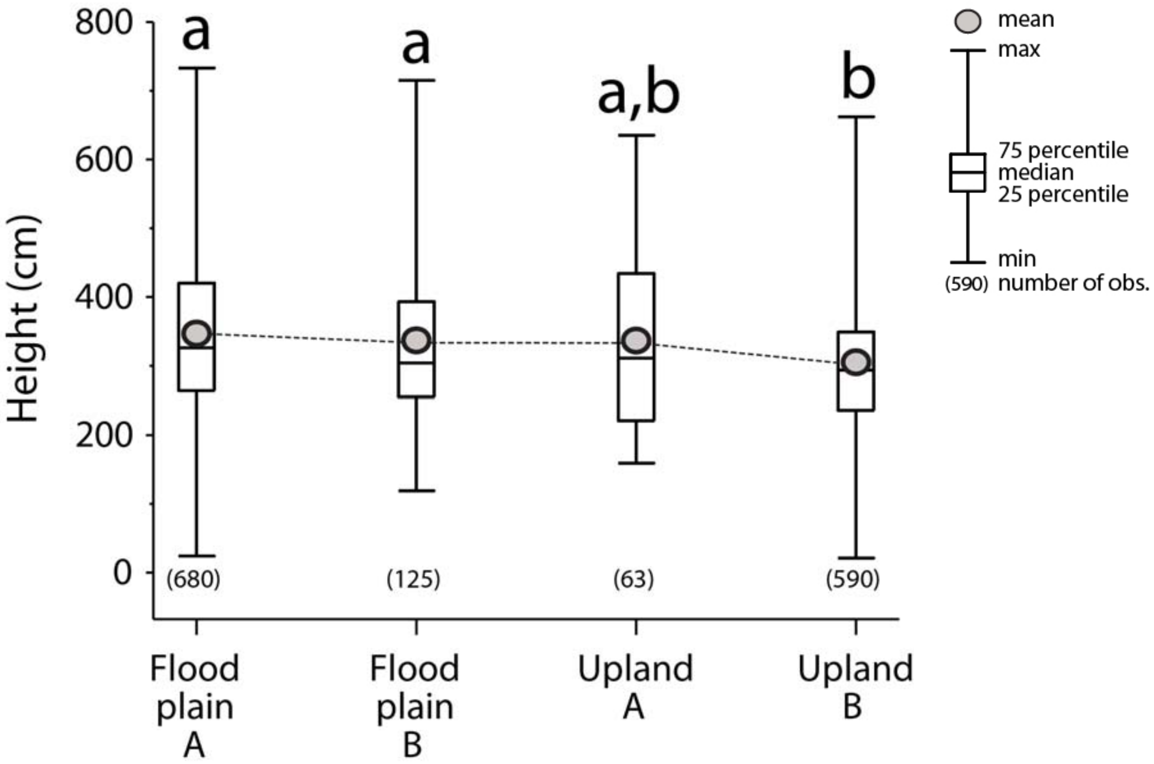

Figure S2. Means and related summary statistics for seedling height within each of the 4 geomorphic zones. Means with differing letters were significantly different based on a Tukey's studentized range means test following an ANOVA of log10-transformed heights versus geomorphic zones.

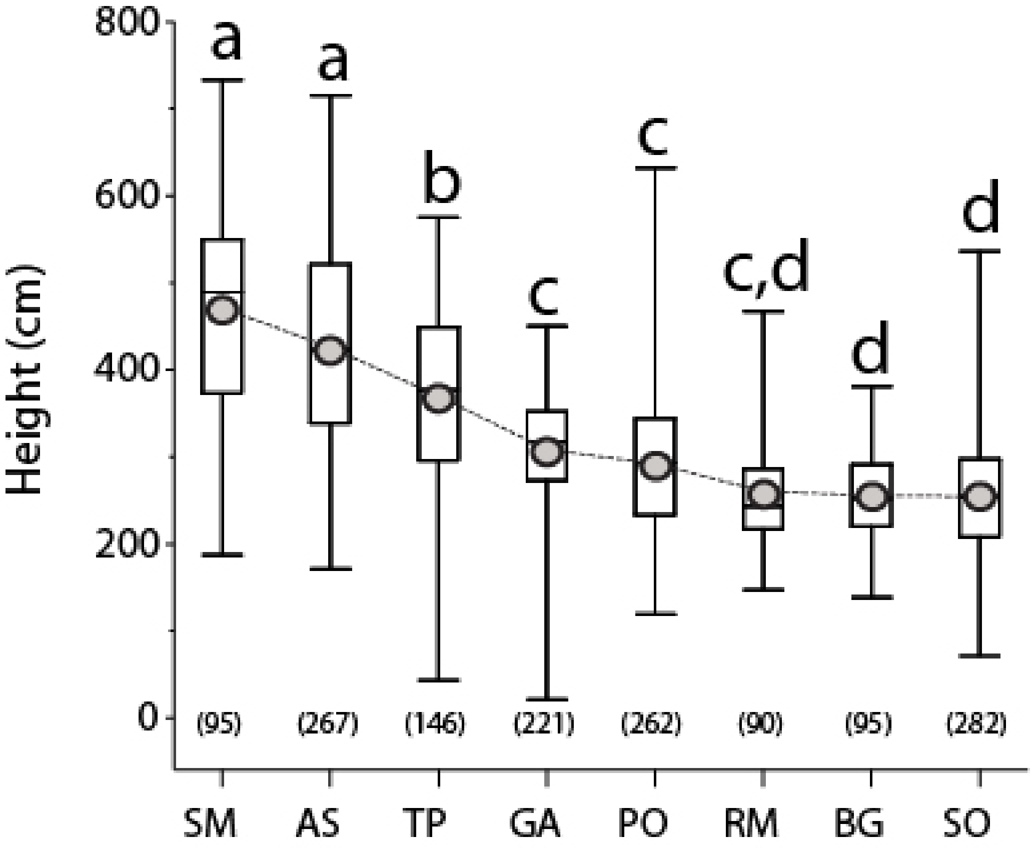

Figure S3. Mean (shaded circle), median (horizontal bar), and 75th and 25th percentile (upper and lower end of box, respectively) of the medial for seedling height by seedling species across the four geomorphic zones. Means with differing letters were significantly different based on a Tukey's studentized range means test following an ANOVA of log10-transformed heights versus seedling species. SM = silver maple, AS = American sycamore, TP = tulip poplar, GA = green ash; PO = pin oak, RM = red maple, BG = black gum, SO = Swamp white oak.