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ORIGINAL PAPER

Tree Growth and Mortality During 20 Years of Managing a Green-Tree Reservoir in Arkansas, USA

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Abstract Green-Tree Reservoirs (GTR) are bottomland hardwood forests that are flooded during late fall and winter to provide waterfowl habitat. Early reports suggested that increased moisture improved tree growth and mast production; however, recent reports showed reduced vigor and growth. This study examines the effects of 20 years of GTR management practices in the Felsenthal National Wildlife Refuge, Crossett, Arkansas. Tree species composition, size characteristics, and vigor classes were measured in 1990, 1995, 2001, and 2006. The overall annual tree mortality rate was 2.6%, with high elevations at 1.7% and low elevations at 3.1%. Annual mortality rates exceeded 3% for willow oak (*Quercus phellos*) and water hickory (*Carya aquatica*), while rates for Nuttall oak (*Q. texana*), overcup oak (*Q. lyrata*), and sweetgum (*Liquidambar styraciflua*.) were lower at 2.8, 2.4, and 1.5%, respectively. Tree health (vigor) has degraded substantially for over 60% of trees initially rated in good or fair condition. Statistical probit models were generated to predict short-term (5 years) and long-term (15 years) vigor degradation. Low numbers of saplings and little advanced regeneration indicated lack of tree replacement, suggesting that inundation strategies of the GTR management may have long-term impacts on forest structure and composition in the southeastern United States.

Keywords Forested wetlands · Predictions · Probit analysis · Vigor

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Introduction

Seasonal impoundments in bottomland forests, called green-tree reservoirs (GTR), were developed in Arkansas during the 1930s to improve waterfowl habitat. In general, GTRs are scheduled to be flooded after trees become dormant in the fall and drained before trees become physiologically active in spring, a flooding schedule that imitates natural patterns. In theory, fall and winter flooding should not harm dormant bottomland hardwood tree species. Dormancy in trees, however, is a condition where complex metabolic processes in buds and twigs take place to prepare the tree for the next growing season (Perry 1971). Thus, species-specific variations in the timing of dormancy do not always coincide with flooding schedules in a GTR.

Early accounts of GTR management suggested that these impoundments were beneficial to tree growth and mast production because of the increase in soil moisture (Broadfoot 1958; Minckler and McDermott 1960; Broadfoot 1967). Later reports, however, have shown that GTR management has reduced vigor and tree growth (Francis 1983; Schlaegel 1984). Wigley and Filer (1989) found that nearly half of the GTRs they studied showed high levels of mortality and poor regeneration of desirable tree species. Ervin et al. (2006) reported significant differences in species composition between GTRs and natural bottomland forests, with a higher proportion of species that were better adapted to continuously flooded or saturated soils in GTRs.

The timely removal of water in GTRs may be problematic. In the southeastern United States, late winter and spring are periods of high water levels in most streams. Passive removal of water from a GTR during a time of natural high water levels is difficult and can result in continued flooding into the next growing season. Although most bottomland tree species can

withstand limited spring flooding, long-standing water that persists into the growing season can be detrimental so that prolonged damage can be severe if the GTR is flooded yearly (King 1995).

Green-tree reservoirs are usually implemented in forest stands with high proportions of trees that are desirable as food sources for waterfowl, such as Nuttall oak (*Quercus texana*) and willow oak (*Quercus phellos*). Several researchers (Smith 1986; Newling 1981; Karr et al. 1989; Ervin et al. 2006) have shown definitive shifts in tree species composition in GTRs towards tree species that are more water-tolerant but less desirable for waterfowl, such as overcup oak (*Quercus lyrata*), water hickory (*Carya aquatica*), water elm (*Planera aquatica*), and buttonbush (*Cephalanthus occidentalis*). The general objectives of this study were to evaluate tree growth and mortality at the GTR in Felsenthal National Wildlife Refuge (NWR) and to relate changes in the forest structure and composition to the flooding strategies of GTR management over an extended time period. Tree metrics and overall tree health expressed as vigor were measured and applied in predictive statistical probit models to project short-term and long-term tree health that may be useful in assessing management practices at the GTR.

Study Site

Felsenthal NWR was established in 1975 and covers portions of Ashley, Bradley, and Union counties in south central Arkansas, at the confluence of the Ouachita and Saline Rivers (Fig. 1); this 26,000-ha refuge was created in part to offset the impacts from the Ouachita-Black Rivers Navigation Project developed by the U.S. Army Corps of Engineers. The first lock and dam (1925) created a permanent pool that inundated 2,000 ha of forest at an elevation of 18.8 m MSL. A second lock and dam ("Felsenthal dam") replaced the first dam in 1985; raising the pool elevation to 19.8 m MSL and increasing the permanent pool to 6,000 ha (Fig. 1). The Felsenthal dam is designed to maintain an ~3-m deep channel for barges and to seasonally raise water levels to 21.3 m MSL, inundating an additional 8,500 ha currently managed as the GTR at Felsenthal NWR. Annual variation patterns in water levels recorded at the Felsenthal dam have shown similar patterns of fluctuation for pre and post 1985 dam operation but with an apparent shift in base water levels from 18.8 m to 19.8 m of the dam (Fig. 2). The daily average water levels reflect flooding in pre and post 1985 dam operation (Fig. 3).

The GTR can become flooded annually beginning in November, with water depth from a few centimeters to more than three meters when the level at the Felsenthal dam is 21.3 m. This area increases by another 7, 700 ha if water levels reach 22.9 m (Fig. 1). Since the Felsenthal NWR is 22.4 km in length (north to south), water levels can vary considerably

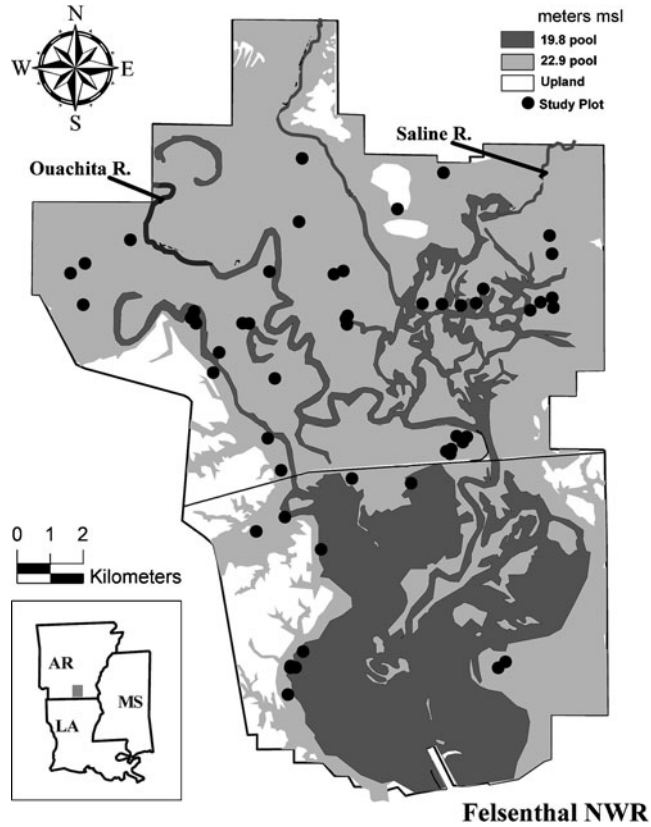

Fig. 1 Map of Felsenthal National Wildlife Refuge showing locations of plots and pool

throughout the refuge and are reflected in the different patterns observed in the growth and survival of the trees.

The GTR at the Felsenthal NWR differs from others in the southeastern U.S. because it was created by damming the Ouachita River rather than diverting water into an area surrounded by low levees. This has resulted in a system through which water is constantly flowing. In addition, the Saline River flows into the Ouachita River from the east. Since there are no dams on the Saline River, precipitation also plays an important role to influence immediate short-term fluctuations in water levels at the GTR. While flowing water may lessen the impacts of long-term flooding on the trees (Kozlowski 2002), it also makes control of the water levels in the GTR more difficult. In several cases the natural river flood conditions have overridden management attempts to maintain or lower water levels at designated times.

Three forest types dominate the GTR at Felsenthal NWR. The overcup oak—water hickory (*Q. lyrata—Carya aquatica*) forest type covers the largest area of approximately 7,600 ha of backwater basins and poorly-drained flats. The sweetgum—Nuttall oak—willow oak (*Liquidambar styraciflua—Q. texana—Q. phellos*) forest type predominates in better-drained locations (7,300 ha). The cypress—tupelo (*Taxodium distichum—Nyssa aquatica*) forest type occupies the lowest elevations and covers only about 400 ha. It occurs

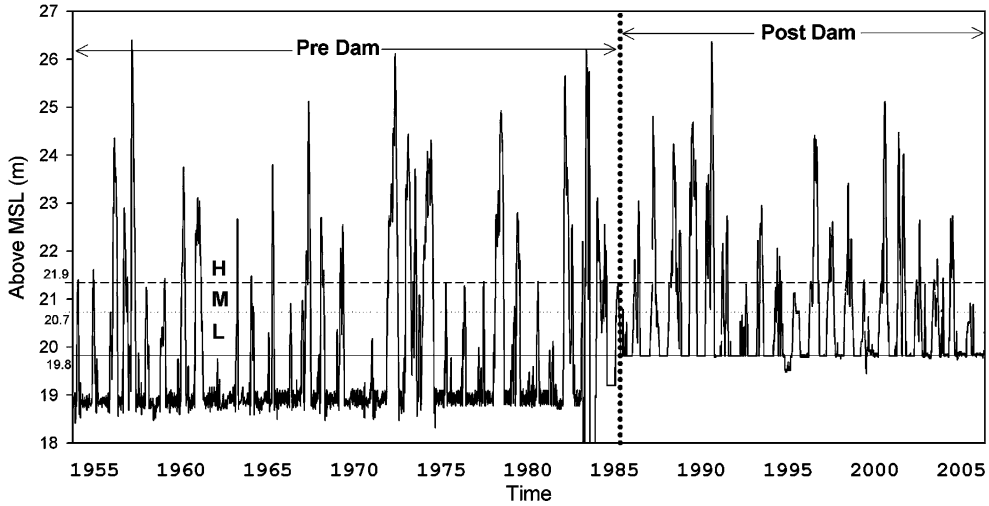

Fig. 2 Yearly water fluctuations in water depth at the Felsenthal lock and dams 1955–2006. Lines marked across the years represent the elevation classes as H (high), M (mid), and L (low) used to describe flooding

in sloughs and areas along the border of the permanent pool that have generally saturated soils.

Before the establishment of Felsenthal NWR, the bottomland forests were harvested commercially. With a combination of different cuts (basal area, stem density, species-specific, as well as clear cuts), up to 50% of the forest was severely altered at the time this study was initiated. Effects from the cuts may still be occurring.

Soils across the GTR are predominately of the Guyton series (Typic Glossaqualfs) and are very deep, poorly drained to very poorly drained, and slowly permeable (Soil Survey Staff 2008). These soils were formed in thick, loamy sediments on local stream flood plains and in depression areas on late Pleistocene age terraces of the coastal plain, where slopes range from 0 to 1%. Guyton series soils resemble silt loams that dry fast especially on higher sites. Other important soil types in the GTR are the Amy (Endoaqualfs alluviam) and Una (Typic Epiaquepts).

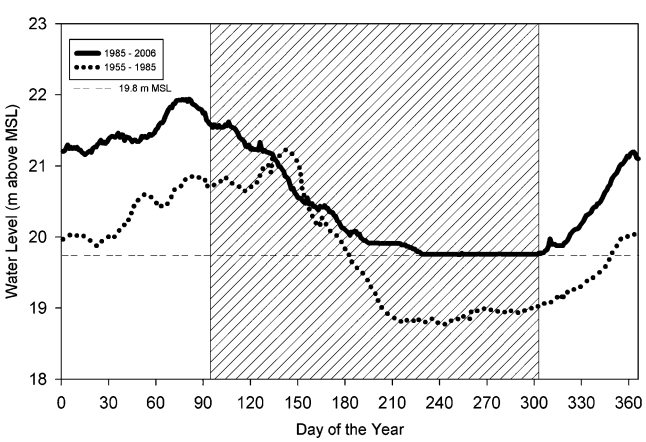

Fig. 3 Daily average water levels at the Felsenthal lock and dam. Pre and post dam water levels are shown as well as the time of year the Felsenthal NWR management targeted the water to be at 19.8 m (shaded area for approx. days 90–300 in the 1995–2000 time period). The excess of water observed in the shaded area as higher levels in the post dam years is caused by natural events

Both of these soil types share some of the same characteristics as the Guyton and can also dry quickly and lead to drought-like conditions in the warmer months.

Plot Design and Distribution

Since 1990, 53 permanent study plots throughout the GTR at Felsenthal NWR (Fig. 1) have been measured every 5 or 6 years. These plots originally intended to provide information on selected forest stands with similar habitat conditions considered representative and desirable for forest management (Teaford 1989). Control plots were not established for this study since the adjacent forests were found to be unsuitable. The plots were not equally distributed in the refuge and not necessarily evenly across the elevation gradients within the refuge. Elevation classes were defined in reference to the flooding regime in the GTR as *low* (19.8–20.7 m), *mid* (20.8–21.3 m), and *high* (>21.3 m), with plots dispersed in the elevation classes as 24 in low, 15 in mid, and 14 in high. Beginning in 2001, there were a series of tree cuts within the GTR that resulted in the thinning of trees in seven plots; subsequently only 46 un-thinned plots were used in all analyses of this manuscript for all measurement years. Circular plots (100-m^2) were sampled within the thinned and adjacent un-thinned plots to measure the impacts that thinning operations may have had on seedling and sapling numbers.

The permanent study plots were square (0.1 ha), containing six subplots. Plots were sampled in the fall prior to flooding in 1990, 1995, 2001, and 2006. Trees with diameters >5 cm were individually numbered and tagged. Saplings of trees and shrubs (<5 cm dbh and >1.4 m in height) were sampled in a 0.025-ha sapling subplot located at the center of the main study plot. Herbaceous plants/trees (seedlings) were sampled in five subplots (1 m^2), located at the center and at each of the four corners of the main plot.

Measurements

Diameter at breast height (dbh), vigor, and crown class for individual trees were collected at the time of each measurement. Dbh was recorded to the nearest mm and measured at the height of 1.4 m. Vigor, a measure of tree health, was assigned class values of 1 to 4 representing percentage of limb loss (dieback) for an individual tree: <5% as 1 (good), 5–25% as 2 (fair), 26–95% as 3 (poor), and >95% as 4 (dead). Crown class followed the traditional assignment method corresponding to light availability in four categories; *suppressed* (S), *intermediate* (I), *codominant* (C), and *dominant* (D) (Smith 1986). Sapling heights were measured in the sapling subplot and woody seedlings were counted in the herbaceous subplots. Measurements were taken in September and October before leaf fall and the rise of water in November.

Fluctuations in elevation (sediment accretion or erosion) were measured using iron pipes, 91-cm long sections of 2.5-cm width, driven into the ground and extending 30.5 cm above the ground at five positions in each study plot. The distance between the top of the pipe and the ground surface was measured to obtain estimates of elevation changes.

Statistical Analyses

Statistical analyses for basal area and stem density were performed on the relative difference (% change) between 2006 and 1990 data only. These included paired t-tests and analysis of variance to test differences overall, among elevations, and among species or species groups (primary species versus all other species). Multiple (Duncan's Multiple Range test) or pairwise (with Bonferroni correction) comparison tests were used where effects were significant.

Mortality rates were calculated for the five primary overstory species from data on the number of live trees of each species (excluding new recruits) at each measurement. The number of live trees in 1990 was used as the baseline. The annual mortality rates were calculated by dividing the total percentage of dead trees to baseline for the time period by the number of years in that period. Analysis of variance was applied to test for differences in overall mortality rates for 1990–2006 among the species and elevations. Likewise, multiple or pairwise comparison tests were used where effects were significant.

Probit analyses were performed over the time period of the study: short-term analyses (2001–2006) and long-term analyses (1990–2006). The probit procedure (SAS Institute Inc. 1999) computes maximum-likelihood estimates of regression parameters for qualitative/discrete responses. The probit models developed in this study defined vigor class as the multinomial, discrete response variable and stem density, diameter class, crown class, and elevation class as regression variables for live trees in the GTR. The continuous stem density measurement was used, but the continuous dbh measurement was redefined into three diameter classes as *small* (<15 cm), *medium* (15–30 cm), and *large* (>30 cm). Definitions of other class variables are given in previous sections: crown class as *suppressed* (S), *intermediate* (I), *codominant* (C), and *dominant* (D), and elevation class as *low* (19.8–20.7 m), *mid* (20.8–21.3 m), and *high* (>21.3 m). The asymmetrical Gompertz cumulative distribution function, $F(x) = 1 - \exp(-\exp(x))$, was applied since there was a skewed distribution of trees moving towards higher, less-healthy vigor classes (deterioration) with time. The objective of the probit analysis was to obtain probabilities for predicting tree mortality in the near future provided that forest conditions remain constant (up to 15 years). These probabilities represent the chance of moving from the existing vigor class level to another level. For short-term analysis, the last period of 2001–2006 was selected since it represented water management conditions that are now current at the GTR. Data from the short-term analysis can be used to help predict vigor and mortality changes that may occur in 2011, whereas the long-term data can give a more precise prediction of the forest status in 2021.

Predictions based on the probabilities for an individual tree, areas of trees, and overall forest health may be generated using the probit model equations. For individual trees, the actual dbh and crown classes for the tree as well as the stem density and elevation class of its plot or comparable area are used to compute the probability that the tree will remain in its current vigor class or change to other vigor classes. Estimates of the general probability for an area dominated by the primary species of similar metrics can be computed by applying the mean, median, or mode values of measurements for that area in the probit equations. To construct tables of finite probabilities, the continuous variables may be categorized into finite classes. The probabilities are averaged within the new class and represent a reasonable estimate over that combination of class variables. Probabilities may be further collapsed by averaging over broader classes.

The level of significance was α=0.05. All statistical analyses were performed using SAS (Version 8) (SAS Institute Inc. 1999).

Results

Species Composition, Basal Area, Stem Density, and Diameter Distributions

The forest stands represented mature trees of approximately 50–75 years in age at the start of this study. Forest composition differed little between the plots within an elevation class. There were 19 tree and shrub species observed in the study plots at Felsenthal NWR (Table 1). Of these, five tree species

Table 1 Basal area (m^2/ha) and stem density (ha) for 19 tree and shrub species found in the 46 un-thinned plots by measurement year. Primary species are denoted in bold. Species: nonexistent in plots are marked as "—", 1 or 2 trees in plots were listed as "<0.01"

		BASAL AREA (m^2/ha)				STEM DENSITY (ha)			
Species	Common Name	1990	1995	2001	2006	1990	1995	2001	2006
Acer saccharum Marsh.	sugar maple	0.03	0.01	–	–	0.4	0.2	–	–
***Carya aquatica* (Michx. f.) Nutt.**	**water hickory**	**1.44**	**1.47**	**1.33**	**1.17**	**45.5**	**38.5**	**32**	**27.3**
Celtis laevigata Willd.	sugarberry	0.01	0.01	0.01	<0.01	0.2	0.2	0.4	0.2
Cephalanthus occidentalis L.	buttonbush	–	–	–	<0.01	–	–	–	0.2
Cornus foemina Mill.	swamp dogwood	–	–	–	<0.01	–	–	–	0.2
Crataegus L.	hawthorn	0.18	0.15	0.13	0.13	23.8	17.8	15.7	16.1
Diospyros virginiana L.	persimmon	0.38	0.35	0.34	0.37	39.7	33.7	32.2	27.5
Forestiera acuminata (Michx.) Poir.	swamp privet	0.16	0.17	0.11	0.12	27.9	19.3	19.3	21.1
Fraxinus pennsylvanica Marsh.	green ash	0.26	0.24	0.22	0.14	7.1	5.2	3.9	2.8
Gleditsia tricanthos L.	honey locust	0.02	<0.01	–	–	1.1	0.2	–	–
Ilex decidua Walt.	deciduous holly	0.22	0.2	0.21	0.22	54.8	47.7	57.1	61.7
***Liquidambar styraciflua* L.**	**sweetgum**	**2.13**	**2.14**	**2.16**	**2.27**	**26.9**	**24.9**	**23.6**	**23.8**
Nyssa sylvatica Marsh.	blackgum	0.03	0.03	0.04	0.04	0.6	0.6	0.9	0.9
Planera aquatica J.F. Gmel.	water elm	0.07	0.07	0.06	0.07	9.9	8.2	6	6.4
***Quercus lyrata* Walt.**	**overcup oak**	**8.86**	**9.74**	**10.79**	**10.51**	**188.4**	**167.3**	**140.5**	**126.1**
***Quercus phellos* L.**	**willow oak**	**9.43**	**9.09**	**9.68**	**9.33**	**86.1**	**67.9**	**55.2**	**52.6**
***Quercus texana* Buckley**	**Nuttall oak**	**6.25**	**6.14**	**6.84**	**6.4**	**67**	**52.2**	**51.1**	**44.9**
Taxodium distichum (L.) L.C.Rich.	baldcypress	0.15	0.16	0.18	0.18	1.5	1.3	1.5	1.7
Ulmus americana L.	American elm	0.03	0.02	0.02	0.02	1.7	1.1	1.1	1.1
	TOTAL	29.69	30.02	32.14	31.03	582.8	486.4	440.6	414.6

are considered the primary bottomland hardwood species: Nuttall oak, overcup oak, willow oak, sweetgum, and water hickory. In 2006, these overstory species made up approximately 80% of the basal area and 40% of the stem density at Felsenthal NWR. Two other bottomland hardwood species, water oak (*Quercus nigra* L.) and bottomland post oak (*Quercus similis* Ashe), found in the Felsenthal NWR were absent from the study plots. American snowbell (*Styrax americanus* Lam) was only large enough to be counted in sapling and herbaceous subplots.

Over 1990–2006, stem density numbers have significantly declined overall (P=0.0051) by 29% (Table 1). There was no significant difference in the decline of stem density numbers for the five primary species as a group versus all other species. The five primary tree species jointly decreased 34% in stem density, whereas deciduous holly increased 13%. A slight increase (P=0.0480) in overall basal area (4.5%) was noted, attributed to a large gain in overcup oak (19%).

Basal area and stem density changes are further delineated by elevation for the five primary species (Table 2). Generally, basal area increased in primary species except water hickory for the high and mid elevations, and decreased for low elevations except overcup oak (P<0.05). Basal areas of water hickory significantly decreased at all elevations, whereas basal areas of overcup oak significantly increased at all elevations (P<0.05). Stem densities differed significantly among the elevations (P=0.0331) with the greatest decline (1990–2006) in the low elevations (high at −17%, mid at −29%, and low at −46%). At the low elevation, the steepest declines (1990−2006) for stem density (P=0.0016) were in willow oak (−61%) and water hickory (−56%), followed by Nuttall oak (−47%), overcup oak (−40%), and sweetgum (−27%). At the mid elevation, the stem density decline (1990–2006) for willow oak (−48%) was significantly greater (P=0.0069) than in the other primary species (−13 to −29%). At the high elevation, there were significant differences (P= 0.0284) among four of the five primary species that showed declines in stem density (1990–2006): water hickory (−37%), willow oak (−33%), sweetgum (−14%), and overcup (−13%). Nuttall oak, however, increased (+9%).

Overall diameter distributions of species in 1990 and 2006 are given in Table 3, where the number of stems per ha are divided into 10 diameter classes. A general decrease (1990–2006) in the number of stems was observed with shifts to larger average diameters for all oaks.

Mortality Rates

Overall mortality rates between 1990 and 2006 were at 2.6% and were greater (3.1%) at low elevations and less

Table 2 Basal area (m^2/ha) and stem density (ha) by elevation class for the five primary species at Felsenthal NWR

Species	Year	BASALAREA (m^2/ha)			STEM DENSITY (ha)		
		High	Mid	Low	High	Mid	Low
Water hickory	1990	0.16	0.55	0.73	4.1	18.7	22.8
	1995	0.18	0.56	0.73	3.9	17.2	17.4
	2001	0.14	0.53	0.65	3.4	15.0	13.5
	2006	0.07	0.51	0.54	2.6	13.3	10.1
Sweetgum	1990	1.33	0.59	0.20	14.2	11.2	1.5
	1995	1.38	0.63	0.13	13.7	9.9	1.3
	2001	1.37	0.70	0.09	13.3	9.2	1.1
	2006	1.40	0.69	0.10	12.2	8.4	1.1
Overcup oak	1990	1.49	2.37	4.99	12.7	40.8	134.9
	1995	1.65	2.67	5.42	12.2	38.2	116.8
	2001	1.88	2.96	5.95	11.4	33.1	96.0
	2006	1.88	2.86	5.70	11.0	28.8	80.8
Willow oak	1990	3.92	3.57	1.93	25.8	37.4	23.0
	1995	3.77	3.57	1.75	21.7	30.3	15.9
	2001	4.11	3.83	1.74	19.5	23.6	12.0
	2006	4.01	3.69	1.49	17.4	19.5	9.0
Nuttall oak	1990	0.65	1.48	4.12	4.3	13.3	49.4
	1995	0.61	1.45	4.08	3.7	11.2	37.4
	2001	0.75	1.68	4.41	5.2	13.3	32.6
	2006	0.77	1.55	4.02	4.7	11.6	26.4

(1.7%) at high elevations for all five primary species (P= 0.0259) (Table 4). There were significant differences (P= 0.0354) among the five species; willow oak and water hickory had the highest overall mortality rates (~3.0%), while sweetgum the lowest rate (1.5%).

Vigor Class

In general, vigor gradually declined from 1990 to 2001 and showed a rapid degradation after 2001. There were slight changes in stem/ha within each vigor class between 1990 and 1995, moderate changes by 2001, but rapid changes by 2006 (Table 5).

Short-term (2001–2006) and long-term (1990–2006) predictions for vigor class are generated from the statistical probit analysis using measurements from approximately 2000 individual trees of the five primary species. Probit models with significant parameters are fitted.

Table 6 represents all stem density, dbh, crown class, and elevation data collapsed (averaged) within a vigor class as a generalized prediction for that vigor class.

The computed probabilities associated with vigor class primarily demonstrate the degradation of trees over time from good condition (vigor class 1) to poor condition or dead (vigor classes 3 or 4) (Table 6). In the short-term future, a tree in good health (vigor class 1) has slight chances of remaining in the same condition or dying (<10%), but moderate chances each of degradation to fair or poor health (vigor classes 2 or 3). Likewise, there is a moderate chance of a tree in fair health (vigor class 2) degrading to poor health (vigor class 3) but a greater chance (~20%) of dying. A tree in poor health (vigor class 3) has a ~60% chance of dying. Comparisons of model predictions with actual data observed between 2001 and 2006 suggest a good fit with differences in values <10%.

For the subset of large primary species trees with large dbh and dominant/codominant crown classes, there is a greater chance of a tree to degrade or stay in fair health (vigor class 2) (Table 6). The chance of dying is <10% overall. There were no vigor class 3 trees in this subset. Larger trees deteriorate more slowly than the general population and are subject to less mortality.

For long-term predictions, the chance of dying is great for any vigor class (Table 6). About 30–50% of the trees are expected to die that were initially rated as in good or fair condition (vigor classes 1 and 2). Almost all trees rated initially as in poor condition (vigor class 3) will die in approximately 15 years. For the large primary species trees, again deterioration is slower and the chance of dying is less (15–30%). Likewise, there is a very good fit (within a few %) of the long-term model predictions with actual data observed between 1990 and 2006.

Table 3 Number of stems (ha) present in 10 diameter classes of 10 cm each, by year (1990 and 2006) and species in the 46 unthinned plots. Species that were found in only one of the 2 years or with <5 stems per ha are not shown in this table

		Diameter Class (cm)									
Species	Year	10	20	30	40	50	60	70	80	90	100
Water hickory	1990	23.8	13.7	3.7	3.2	1.1					
	2006	12.7	7.9	2.8	2.4	1.1	0.4				
Hawthorn	1990		22.3	1.5							
	2006	15.2	0.9								
Persimmon	1990	33.7	5.2	0.6	0.2						
	2006	23.4	3.0	0.4	0.4		0.2				
Swamp privet	1990	26.8	1.1								
	2006	20.8	0.2								
Green ash	1990		3.4	2.6	0.2	0.4	0.4				
	2006		1.3	0.6	0.4	0.2		0.2			
Deciduous holly	1990	54.3	0.2	0.2							
	2006	61.6									
Sweetgum	1990	5.4	6.4	5.8	5.6	2.4	0.9	0.4			
	2006	4.3	6.4	4.1	3.9	3.0	1.3	0.9			
Water elm	1990		9.0	0.9							
	2006		5.2	1.3							
Overcup oak	1990	76.2	68.5	20.0	9.5	7.5	4.3	1.9	0.4		
	2006	21.3	44.2	27.7	13.5	7.7	6.4	4.3	0.9		
Willow oak	1990	5.2	20.2	23.2	18.9	10.1	5.8	2.1	0.2	0.4	
	2006	6.7	2.8	8.4	9.5	10.3	7.9	4.5	1.7	0.4	0.4
Nuttall oak	1990	2.8	15.2	24.5	15.7	5.2	2.8	0.6	0.2		
	2006	5.6	2.4	7.1	13.5	9.5	4.3	1.1	0.4	0.4	
Baldcypress	1990	0.9			0.2		0.4				
	2006	0.9	0.2		0.2		0.2	0.2			

Regeneration

The number of oak seedlings exceeded that of the other woody species by about 10 times in 1990, then declined to its lowest levels in 2001, followed by a slightly rise in 2006 (Fig. 4). On the other hand, saplings (2.5–5.0 cm dbh) of oaks or other tree species were rarely found in the sapling subplots. There were 13.6 oak saplings per hectare in 2006.

Fluctuations in Elevation

The net change in elevation over all study plots appears to be minimal at −0.01 cm in 1995, −0.16 cm in 2001, and −0.12 cm in 2006, with the net change of −0.09 cm over all years of the entire period. The overall sedimentation rate appeared to be similar to other studies (Hupp and Morris 1990). Although there were plots with up to 13 cm of sediment accumulated during any one time period, this gain was often offset by a smaller measurement observed in the following time period that represented a modest amount of erosion. Thus, changes in soil elevation do not appear to be an important factor contributing to mortality or degeneration of trees within elevation classes.

Discussion

After two decades of GTR management, mortality of mature trees has continued and was 2 to 3 times greater than normally expected mortality rates of similar bottomland forests. Advanced regeneration has been inhibited by increased flood duration, reducing the recruitment of trees into the forest. The decline in stem density numbers was directly related to tree mortality experienced in this GTR. Basal area of surviving trees has increased during the time of this study, but there has been no overall net basal area gain due to reduced stem density.

The basal area measurements taken in 1990 and 1995 showed essentially no overall net increase in basal area (Allen et al. 1996) (Table 1). In 2001, the basal area of the overstory increased substantially over the 1990 and 1995 levels but with decreased vigor, and appeared to coincide with ranges reported in other studies of unmanaged bottomland hardwood stands (Southern Hardwood Forestry Group 1967; Teaford 1989; Allen 1992). There was, however, a decline in basal area observed in 2006, partially attributed to the loss of overcup and willow oaks especially in the low elevations. Overcup oaks have a moderate

Table 4 Number of trees in 1990 and subsequent annual mortality rate per time period and elevation class of trees >5 cm (2 in) diameter-at-breast height for primary bottomland hardwood tree species at Felsenthal NWR (46 un-thinned plots only). Annual mortality rates were calculated by dividing the observed mortality rate at the end of each period by the number of years in that period. Data do not include recruitment. Overall percentages of mortality and mortality rates are given for the 1990–2006 period per species and species total

Primary Species	Elevation Class	1990 Trees	1990–1995 Annual	1995–2001 Annual	2001–2006 Annual	1990–2006 Overall % (%/yr)
Water hickory	High	19	1.1	1.8	4.2	36.8 (2.3)
	Mid	87	2.3	2.5	2.1	36.8 (2.3)
	Low	108	4.8	3.9	3.0	62.0 (3.9)
Sweetgum	High	66	0.9	1.5	1.5	21.2 (1.3)
	Mid	52	2.3	1.0	1.5	25.0 (1.6)
	Low	7	2.9	2.4	0	28.6 (1.8)
Nuttall oak	High	20	5.0	0	1.0	30.0 (1.9)
	Mid	62	3.5	0.5	2.3	32.3 (2.0)
	Low	230	4.9	2.0	2.6	49.1 (3.1)
Willow oak	High	120	3.2	1.8	1.7	35.0 (2.2)
	Mid	174	3.8	3.1	2.2	48.3 (3.0)
	Low	122	5.7	2.5	3.0	61.5 (3.8)
Overcup oak	High	59	0.7	1.4	1.0	16.9 (1.1)
	Mid	190	1.4	2.2	2.1	30.5 (1.9)
	Low	578	2.8	2.9	2.5	43.8 (2.7)
TOTAL	High	284	2.1	1.5	1.6	27.8 (1.7)
	Mid	565	2.6	2.2	2.1	36.6 (2.3)
	Low	1045	3.8	2.7	2.7	48.8 (3.1)
	Overall	1894	3.2	2.4	2.3	42.0 (2.6)

tolerance for shading and flooding (Hall and Harcombe 1998). Deciduous holly, baldcypress, and black gum are species showing slight increases in growth and numbers of stems since 1990 (Table 1), which may be responding with increased growth to the additional light caused by the mortality of larger trees.

There has been a major overall decline (~30%) in stem density numbers since 1990, with the greatest decline at the lowest elevations. All oak species suffered major losses at the low elevations. Stem density losses were less at higher elevations, where Nuttall oak showed a slight increase of 9%.

Table 5 Stem density (ha) for all species in vigor classes 1–3 from 1990 to 2006 at Felsenthal NWR, by elevation and crown class

		Vigor Class 1				Vigor Class 2				Vigor Class 3			
Elevation	Crown Class	1990	1995	2001	2006	1990	1995	2001	2006	1990	1995	2001	2006
High	Dominant	9.0	9.0	7.6	2.0	1.0	0.3	4.0	9.7	0.0	0.0	0.0	3.0
	Codominant	35.7	32.3	17.6	1.3	8.3	8.0	16.0	16.3	0.0	0.3	0.0	12.7
	Intermediate	18.0	13.7	9.3	0.0	5.3	7.0	17.0	20.3	0.3	0.0	0.3	26.3
	Suppressed	64.0	37.0	23.0	0.3	45.6	56.3	71.6	13.7	2.3	3.0	3.3	64.3
Mid	Dominant	9.3	9.6	8.5	1.6	2.4	1.3	4.0	11.5	0.0	0.0	0.0	3.5
	Codominant	44.0	38.1	24.2	1.1	6.1	7.7	12.8	16.0	0.8	0.5	0.0	12.3
	Intermediate	27.2	21.9	12.0	1.3	8.5	10.4	18.9	13.3	0.0	0.3	0.5	23.2
	Suppressed	80.3	32.8	23.7	0.8	38.4	67.2	68.8	13.3	6.1	5.3	5.9	62.1
Low	Dominant	9.7	7.8	8.0	0.4	1.7	1.9	5.5	11.2	0.0	0.0	0.0	3.2
	Codominant	54.5	50.7	18.3	3.8	13.0	9.7	33.7	22.5	0.6	1.1	0.2	18.7
	Intermediate	36.6	30.5	10.9	1.1	12.6	9.7	26.5	13.0	0.4	1.3	1.7	28.6
	Suppressed	81.9	51.6	11.4	0.6	55.4	44.8	54.9	9.1	9.5	8.8	12.6	50.1

Table 6 Short-term (2001–2006) and long term (1990–2006) vigor class predictions for the five primary species and subset of large-diameter trees with dominant /codominant crown classes, expressed as the percentage (chance) of moving from an existing vigor class (EVC) to a future vigor class (FVC) over all parameter classes combined. For the subset of large diameter trees, there were few vigor class 3 trees (n=2) in 1990 and thus vigor class 3 was omitted. Observed percentages are in parentheses, where existing vigor class corresponds to 1990 (long-term) or 2001 (short-term) vigor class data and future vigor class to 2006 vigor class data

		SHORT–TERM (2001–2006)				LONG–TERM (1990–2006)			
Groups	EVC	FVC 1	FVC 2	FVC 3	FVC 4	FVC 1	FVC 2	FVC 3	FVC 4
Primary Species	1	5 (7)	44 (52)	43 (31)	8 (9)	3 (3)	30 (28)	34 (35)	32 (34)
Primary Species	2	3 (1)	32 (26)	47 (54)	19 (18)	2 (1)	19 (17)	28 (24)	51 (58)
Primary Species	3	1 (2)	11 (4)	28 (31)	60 (63)	0 (0)	1 (2)	2 (0)	97 (98)
Large Diameter	1	7 (8)	57 (58)	34 (25)	2 (8)	6 (6)	46 (46)	36 (27)	13 (20)
Large Diameter	2	5 (3)	43 (44)	45 (42)	7 (10)	3 (1)	30 (37)	36 (28)	31 (35)

Mortality

Estimates of annual mortality rates are uncommon, but average background rates for most forests are about 1% per year or less (Franklin et al. 1987; McCune et al. 1988; Putz and Brokaw 1989; McCune and Henckel 1993). The annual mortality rates observed within the GTR at the Felsenthal NWR were above average (1.7, 2.3, and 3.1%, for high, mid, and low elevations, respectively). Annual mortality rates also differed among elevations and species, and likewise exceeded the expected background rate. The mortality patterns in the oaks observed at Felsenthal NWR are consistent with those observed at other GTRs in the southern USA (Newling 1981; Karr et al. 1989; Young et al. 1990; King 1995). Continued annual flooding at Felsenthal NWR will result in severe additional mortality of primarily willow and Nuttall oaks, followed by overcup oaks. An in-depth discussion of mortality for each of the five primary species follows.

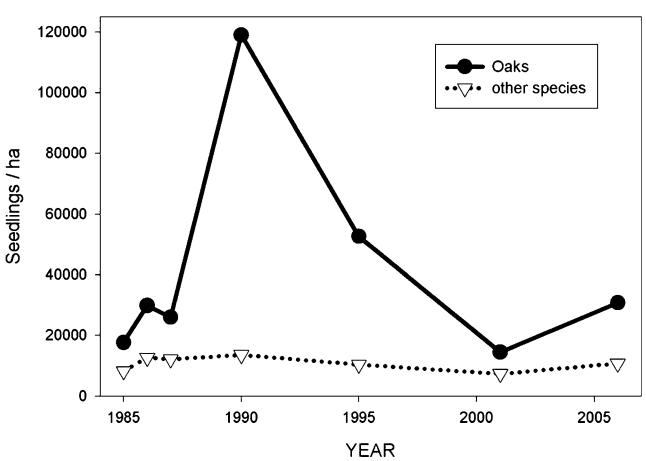

Fig. 4 Numbers (seedlings/ha) of oak and other woody seedlings (<140 cm tall) estimated from herbaceous plots sampled at each of the measurement years at Felsenthal NWR

Nuttall Oak Annual mortality rates of Nuttall oak trees were high at all elevations (3.5–5.0%) in 1995, decreased by 2001, and then increased in 2006 (Table 4). By 2006, half of the Nuttall oaks died in the low elevation plots and 1/3 of the trees died in each of the mid and high elevation plots. Most of the mortality occurred in small diameter trees (<30 cm); however, the continued growth of the larger trees has resulted in the average diameter shifting from about 32 cm in 1990 to 43 cm in 2006 (Table 3). Although, the number of trees in the small (10 cm) size class showed an increase in 2006 (mid and high elevation plots), the number of trees remaining in this small size class were too few (<0.5/ha per 5-year period) to replace those being lost (Table 3). Few Nuttall oak trees were found in the mid elevation (<4.0/ha) and high elevation (<1.0/ha) plots.

Most of the loss in stem density for Nuttall oak has occurred within the low elevation plots (Table 2). The substantial decrease in the total number of stems in all size classes up through 40 cm and the lack of new stems in the smallest size class indicate a potential problem in the low elevations. Although currently the larger Nuttall oak are increasing in numbers, the overall decrease in the number of stems may lead to poor future regeneration that may affect waterfowl use of the stands. Nuttall oak is an important wildlife species and flooding such as observed in the GTR at Felsenthal NWR has been shown to decrease acorn production by more than 50% (Francis 1983).

Willow Oak Mortality rates were higher in willow oak than for any other species in this study. All mortality rates remained well above background mortality rates for all elevations and time periods (Table 4). More than a 1/3 of the willow oaks died in the high elevation plots, half in the mid elevation plots, and 2/3 in the low elevation plots. Likewise, there was a large decrease in stem density especially in the smaller size classes (Table 3). The loss of small diameter trees together with a shift to a larger

average diameter (38 cm in 1990 to 48 cm in 2006) indicated losses of willow oak stems that are not being regenerated. Willow oak, however, had only moderate losses in basal area (Table 1) and modest increases in the numbers of larger diameter trees (Table 3). Larger diameter willow oak trees (>50 cm) produce greater acorn crops (Goodrum et al. 1971) that are a necessary food source for wildlife in the GTR.

Overcup Oak Overcup oaks were the most abundant tree throughout this study and comprised 30% of all stems in 2006. Of the five primary species, annual mortality rates of the overcup oak were the lowest in 1995 (Table 4). Less than 20% of the overcup oaks died in the high elevation plots, 30% died in the mid elevation plots, and 44% died in the low elevation plots. The diameter distribution for overcup oak shows large numbers of stems in the smaller size classes (Table 3). There were, however, surprisingly high losses of the smallest overcup oaks during the last two measurement periods, especially in the low elevation plots where most of the overcup oaks grow.

Although there were many overcup oak seedlings available to fill gaps left by the death of other tree species, there was little advanced regeneration of overcup oaks. Since the number of small overcup oaks (<10 cm in diameter) in 2006 was less than 1/3 of the number in 1990, there may be fewer of the more-water tolerant overcup oaks to replace the dead and less-water tolerant tree species (Nuttall oak, willow oak, and sweetgum) in the future.

Water Hickory Annual mortality rates of water hickory were severe in the low elevation (3.0–4.8%), and moderate in the mid elevation (2.1–2.5%) (Table 4). At the high elevation, water hickory annual mortality rates started low near background rates in 1995, but increased to severe (4.2%) by 2006. More than 1/3 of the trees died in both mid and high elevation plots, and 2/3 of the trees died in the low elevation plots, where most of the recent mortality has been concentrated in the 10- and 20-cm diameter size classes (Table 3).

Sweetgum Annual mortality rates of sweetgum were close to background (0.9–1.5%) at the high and mid elevations, except at mid elevation in 1995 (Table 4). Only seven sweetgum stems occurred in the low elevation plots of this study and as such, the high mortality rates observed may be misleading. The decline in the number of sweetgum trees was moderate as compared to the other primary species (about 20–30% died in all elevation plots). The relatively uniform distribution of low numbers of individuals (Table 3) and similar mortality rates throughout the size classes suggested little change throughout the study in this species. Sweetgum is both shade intolerant (Lin et al. 2001) and flood intolerant (Hook 1984), whereby an open canopy and reduced flooding are required for seedling establishment and growth. The response of sweetgum in the GTR appeared to support these requirements. Sweetgum has increased only slightly in basal area since 1990 and these gains are in the large (>50 cm) diameter stems.

Other Species The combined basal area of other species was less than 2 m^2/ha and less than 140 stems/ha in 2006 (Table 1). The most abundant species was deciduous holly. Deciduous holly stems will not attain canopy tree status but could shade tree seedlings and rob vital nutrient resources from the tree seedlings and saplings. There have been also slight gains in stem density and basal area for other tree species (blackgum, water elm, and baldcypress) because of the mortality of the primary species that allow additional light and reduce competition for nutrients. Furthermore, the increase in numbers of buttonbush and dogwood in the study plots observed in 2006 could indicate minor shifts such as increased soil moisture caused by flooding. Some species (such as sugar maple and honey locust) were uncommon throughout the GTR but will not likely disappear from the GTR in the future. There were no invasive tree species found in the study plots; however, Chinese tallow tree (*Triadica sebifera* L.) is known to grow in the area.

Vigor

Although vigor is a subjective measurement, it is effective in comparing overall tree health. In 1990, most of the primary species trees (75%) were in good condition (vigor class 1), but <5% of the trees remained in good condition by 2006. There was a gradual decline in vigor observed from 1990 to 2001 but a rapid decrease thereafter. The sharp decline observed in 2006 of stems/ha in vigor class 1 was offset by increases in the stems/ha in vigor classes 2 and 3 (Table 5). Furthermore, a general trend (1990–2006) of decreasing vigor was observed for most species from the dominant trees through the canopy to the suppressed trees: (1) most stems/ha shifted to vigor class 2 in the dominant crown class; (2) the shift was similarly divided between vigor classes 2 and 3 in the codominant crown class; (3) the shift was greater to vigor class 3 in the intermediate crown class; and (4) most stems in the suppressed crown class in 1990 became vigor class 3. Trees that were deteriorating showed signs of disease, especially dieback caused by the fungus *Hypoxylon atropunctatum* that is common to bottomland species of trees under water stress (Tainter and Baker 1996).

The statistical probability model (probit) generated predictions for the chance of changing vigor class over time for trees at Felsenthal NWR. Generally, the trend is from a better vigor class (1 or 2) to a worse vigor class (3 or 4). In 1990, 75% of the primary species trees were in good condition (vigor class 1), but only 3% of the trees remained in good condition by 2006. At the end of 5 years (2011), a dramatic (40–60%) decline in vigor can be projected, mostly to the next lower vigor class. At the end of 15 years (2021), the projected shift should be more severe to lower vigor classes, with high mortality predicted for all vigor classes (30–97%). Thus, there is little chance for trees to remain in good condition or stay in the same vigor class for more than 5 years.

Regeneration

Since the opening of the Felsenthal dam in 1985, numerous woody seedlings were observed in the herbaceous subplots (Fig. 4). Approximately 80% of these seedlings were <50 cm in height. Of seedlings >50 cm in height, only 2% were oak species. Saplings of any kind were rarely found (oak saplings in only 6 plots in 2006). The initial germination of seedlings of desirable oak species continuously occurred but failed to mature due to extended flooding. Furthermore, seedlings of some species were absent (swamp privet, green ash, American elm) and others were low in numbers (hawthorns, deciduous holly, American snowbell). A clear shift, however, in seedling species composition towards flood-tolerant species was not evident.

Possible causes for the reduced numbers in seedlings and saplings were investigated. During the time period of this study, Felsenthal NWR underwent silvicultural treatments, and seven study plots were thinned in 2001. There were no significant differences in seedlings and sapling numbers between thinned and un-thinned plots at any elevation, which suggests that lack of light penetration in un-thinned plots probably did not limit growth of seedlings and saplings. High flooding was a more likely cause for few seedlings surviving more than 1 or 2 years.

Hydrology

Post-dam water levels are generally higher than pre-dam levels, but the pattern of increases and decreases is similar, except at the peak where water levels crest earlier in the post- (~day 75) than in pre-dam (~day 150) conditions. The goal of Felsenthal NWR management is to keep water levels at 19.8 m MSL between approximately days 90 and 300 (shaded area in Fig. 3). Inspection of the hydrograph shows the actual water levels for post-dam (1995–2006) operation are not coinciding with management targets for over half of the time period.

Conclusions

This study has demonstrated that vigor has decreased and subsequent mortality appears to be inevitable for many trees in the GTR at Felsenthal NWR. Stem density has decreased for all five primary species but basal areas increased by 2006 from 1990. This pattern is consistent with earlier studies conducted on the GTR (Allen 1992; King 1995; Allen et al. 1996); however, earlier studies could not forecast the extent of the acceleration in tree health deterioration after 2001. This long-term response of trees indicates the inability of the trees to finally adapt successfully to different flooding regimes. The most abundant species, overcup oak (flood tolerant), seems to be best suited for the current hydrological conditions throughout most of this GTR. Between 1985, when the Felsenthal dam was put into operation, and 2006, more than 1/4 of all trees in the GTR have died, and are mostly of the five primary species with little or no advanced regeneration. Despite indications that the high rates of tree mortality may be leveling off, trees are still dying at rates higher than expected background estimates for most forests and likewise will continue into the future.

Tree health or vigor over 1990–2006 was statistically analyzed to generate a matrix of probabilities via probit models for predicting the chance of improvement or deterioration of a tree given specific tree metrics and initial vigor condition. Analyses were restricted to the subsets of five primary species and large trees of said species. The application of these probabilities to individual trees of the primary species or to areas dominated with these species of similar metrics within the GTR could help the refuge management to select or prioritize trees or areas for silvicultural operations. Extrapolation of these data to other parts in the GTR of Felsenthal NWR seems reasonable since refuge personnel and other professional foresters have observed similar dynamics of survival, vigor, and growth from plots in other areas of the refuge.

Since 2001, a new water management schedule allows for lower water levels during the flooding season and starts the water level increase at the end instead of the middle of November. The target water levels will not exceed 21.0 m MSL or 0.3 m less than the previous level. A change of 0.3 m in water levels implies that water can be removed more quickly, so that thousands of hectares of forest may be flooded less often and for shorter durations. Although slight, these adjustments could be important changes for limiting stress from flooding on trees, thereby potentially improving their vigor and increasing long-term survival of seedlings. The long-term effect of this new flooding regime will require more time to fully assess its impact on deceleration, if any, in the mortality rate of trees to produce a more stable forest environment.

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