This is not a peer-reviewed article.
Hydrology and Management of Forested Wetlands
Proceedings of the International Conference 8-12 April 2006
Publication Date 8 April 2006
ASABE Publication Number 701P0406.

INFLUENCE OF SOIL PHYSICOCHEMICAL PROPERTIES ON HYDROLOGY AND RESTORATION RESPONSE IN CAROLINA BAY WETLANDS

DE- AI09-00SR22188 Proceedings 2006 06-21-P

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ABSTRACT

Carolina Bays are shallow depression wetlands found in the southeast US that have been severely altered by human activity. The need to restore these complex and diverse systems is well established, but our understanding of basic wetland hydrological processes is limited, hence our ability to predict the need for and/or assess the effectiveness of bay restorations is hindered. Differing physicochemical properties of soils within bay interiors may control bay hydrology. However, previous efforts to establish relationships between soil characteristics and bay hydrology have been inconclusive and the question still remains as to why some bays are ponded throughout the year while others, within a similar landscape unit, are predominantly dry. An assessment of soil and hydrologic characteristics was initiated in restored and unrestored control bays to determine if a relationship exists. Soil morphology was described and permanent monitoring wells were installed at each site. Soil samples were collected by horizon to a depth of 2 meters at the topographic center of each site, and then analyzed. After three years, multiple regression analysis (stepwise backward and forward) was used to establish relationships between the soil physicochemical characteristics and bay hydroperiod in the undisturbed sites. Results from surface soils indicated that exchangeable acidity (EA) was the best single predictor of hydrology. The best double predictor was EA and total N and EA, total N and total C as the best triple predictor. A significant relationship ($r^2 = 0.96$) between hydroperiod and clay content in the argillic horizon (Bt) was also observed. Subsequently, this relationship was utilized to predict hydrologic response using pre-restoration hydroperiod data. The model accurately identified sites that did not need hydrologic restoration (too wet), and effectively showed sites that responded well to restoration activities.

KEYWORDS. Carolina bays, wetland soils, wetland hydrology, wetland restoration.

INTRODUCTION

Hydrology is generally considered to be the primary controlling factor for the development and persistence of wetlands (Kusler and Kentula, 1989; Mitsch and Gosselink, 1993). However, characterizing wetland hydrology is a timely process that is difficult to perform and often compromised due to constantly changing hydrological/environmental conditions and to potential error associated with water budget accounting. The physical and morphological properties of soils within wetland boundaries likely govern hydrologic function; however, information pertaining to which properties are most important in controlling the extent of flooding or inundation is limited. As such, increased efforts to characterize wetland hydrogeology as it is related to soil

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physicochemical properties are needed, particularly as a means for evaluating functional wetland restoration.

Carolina Bays represent one such wetland type that are not only poorly understood with respect to hydrology, but have also been severely altered by human activity (Bennett and Nelson, 1991). Carolina bays are shallow elliptical depressions found in the Atlantic Coastal Plain. These wetlands exhibit a range of moisture regimes from seasonally saturated to semi-permanently inundated (Shalles and Shure, 1989), and are of ecological significance as habitat for several biological communities and rare species (Sharitz and Gibbons, 1982; Knox and Sharitz, 1990; Semlitsch et al., 1996; Krajick, 1997). Although past research has suggested that bays receive water inputs from meteoric, surface and groundwater sources, evidence linking a specific source to bay hydroperiod (length and duration of inundation) is missing. Differing physical properties of soils within and surrounding bay interiors also contribute to the hydrology dilemma. In general, sandy surface deposits in the rims and surrounding uplands characterize Carolina bays. Because of the high permeability associated with sandy soils, overland flow or runoff into bays is uncommon. However, clay content increases with depth in the uplands, and may limit vertical flow and facilitate subsurface lateral movement into some bays (Schalles et al., 1989). The bay interior soils often contain elevated concentrations of clay and less permeable sediments that are conducive for the development of an aquiclude or clay lens. Once developed, vertical infiltration within the depression area decreases and flooding ensues.

Determining whether a site is suited for restoration generally involves an assessment of disturbance level (soils, hydrology, vegetation and wildlife); location and accessibility; and aesthetics. Unfortunately, these activities require a great amount of time and resources. Considering that soil physicochemical properties likely contribute to the length and duration of ponding in Carolina bays, they may provide information to determine if a site is suitable for restoration. In addition, soil features may also provide insight as to why some bays remain ponded throughout the year while others, within a similar landscape unit, are predominantly dry. Given these conditions, a project was initiated with the following objectives: 1) establish relationships between soil physicochemical properties and Carolina bay hydrology, and 2) use the developed relationships to predict the likelihood for hydrologic restoration success in disturbed bays.

MATERIALS AND METHODS

Twenty-two Carolina bays on the Savannah River Site (SRS) were selected as potential study sites. Preliminary studies were conducted at each bay to characterize topography, landform area and soils. Soil samples were collected along transects in all bays from the upland to the bay center. Soil cores were extracted, at each sampling point to a depth of 2.0 meters, described and subsampled by horizon. Subsamples were analyzed for cation exchange capacity (CEC), total exchangeable bases (TEB): soil macronutrients (P, K, Ca, Mg, Na) and micronutrients (Zn, Mn, Cu, B), particle size, pH (1:1), electrical conductivity, and total nitrogen (N) and carbon (C) using standard procedures(NRCS, 1996; Sparks et al., 1996).

Bay hydrology was monitored bimonthly using a combination of staff gages, shallow monitoring wells and semi-continuously recording data loggers with measurements taken at 6-hr intervals. Each site contained well nests within the bay interior, upland zone and a transitional point (hydric soil boundary or abrupt vegetation change). The saturated water depth and bay hydroperiod were determined from measurements accumulated with the above monitoring devices. Open precipitation and throughfall were measured in bay margins and interiors of each site. Other meteorological variables and long-term data were provided by the SRS Weather Center.

Restoration of 16 Carolina bays with functioning drainage ditches began in 2001. Trees in the bay interiors were harvested and drainage ditches were plugged with low permeable clays to re-establish prior hydrological conditions. The six remaining bays were not disturbed and used as unrestored controls. Additional information on restoration treatments and design has been described elsewhere by Barton et al. (2004).

SAS Version 8 for Windows was used for statistical analysis (SAS Institute, 1999) T-tests with unequal variances were performed to determine significant differences between soil parameters among the restored and control bays. Significant differences were tested at $\alpha = 0.05$. Stepwise multiple linear regression models were constructed to examine soil factors that were associated with variations in bay hydroperiod. A significance level of $p < 0.15$ was required for retention in the models of individual parameters and $p < 0.05$ was considered significant for models.

RESULTS AND DISCUSSION

Statistical analyses using T-tests indicated that soils in the restored and control bays were not significantly different for all variables examined. This is somewhat surprising given that the restored bays contained active drainage ditches that were well over 50 years in age. We anticipated that the drier conditions would influence variables such as soil acidity and decomposition, which would be reflected in the soil chemical composition. However, the natural variability in hydrology of these systems is wide enough to include both very dry and permanently ponded bays, as exhibited by the unrestored control bays 57 and 138 (Table 1). In addition, some treatment bays (bays 5, 124, 131and 5016 in 2000) may not have had a very effective drainage system due to natural soil sloughing and accretion and were not hydrologically affected by the drainage ditch even before restoration activities began (Table 1). Pre-restoration hydrology of the bays revealed that most of the treatment bays exhibited a very low hydroperiod (ponded < 10% of year), although some were ponded for a significant portion such as bays 5 and 124 (Table 1). After restoration, the hydrological response to the restoration treatments was complicated by a prolonged regional drought. For the three-year period examined, average monthly rainfall fell below the 50 year precipitation average at SRS for all but 6 months (Table 2). As such, all treatment and reference bays were dry for most of 2002. Surprisingly, however, a change in hydroperiod (% time ponded per year) was detected in many of the treatment bays, and most of the restored bays exhibited an increase in hydroperiod after the treatments had been imposed (Table 1).

Table 1. Three year hydroperiod data for treatment and control bays, and hydroperiod change due to treatment implementation*.

Bay Hydroperiod and Hydroperiod Change Following Restoration

Restored Bays

Bay	**5**	**124**	**126**	**131**	**171**	**5001**	**5011**	**5016**	**5071**	**5092**	**5128**	**5135**	**5184**	**5190**	**5204**	**5239**
2000	0.74	0.56	0	0.44	0.10	0	0.01	0.35	0.02	0	0.01	0.01	0	0	0.12	0.01
2001	0.79	0.67	0.33	0.81	0.23	0.38	0.40	0.41	0.01	0.15	0.67	0.05	0.24	0.28	0.65	0.47
2002	0.81	0.44	0.04	0.51	0.15	0.09	0.02	0.29	0.02	0	0.55	0.04	0.13	0.01	0.52	0.01
$\Delta^{\dagger}$	0.06	0.01	0.19	0.22	0.08	0.23	0.20	0	0.01	0.07	0.60	0.04	0.19	0.14	0.47	0.24

Control Bays

Bay	**57**	**58**	**108**	**118**	**138**	**5055**
2000	0.01	0.08	0.06	0.53	0.64	0.29
2001	0	0.04	0.10	0.49	0.54	0.26
2002	0	0	0	0	0.54	0.06
$\Delta^{\dagger}$	-0.01	-0.06	-0.01	-0.29	-0.10	-0.12

*Hydroperiod change (Δ) is difference in pre-restoration hydroperiod (2000) from the post restoration average hydroperiod (2001 and 2002). Hydroperiod = (fraction of time ponded per year).

Table 2. Average monthly precipitation during the study period and 50 year SRS precipitation average[†].

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	----	----	----	----	----	(mm)	----	----	----	----	----	----
2000[‡]	165.1	31.8	106.4	41.7	10.7	90.9	34.3	67.3	101.3	0.14	54.6	34.0
2001	34.5	53.8	233.5	32.4	91.7	166.1	55.6	79.7	84.0	4.5	28.4	14.4
2002	60.9	10.9	35.5	40.3	41.4	39.6	117.9	112.5	87.9	82.8	82.5	108.4
1952-2001*[‡]	106.6	109.2	127.0	82.6	93.7	115.8	130.8	123.7	103.6	73.9	66.3	88.1

[†]Average monthly rainfall data obtained from rain gauges at the study sites and from two weather stations.

*Average long-term rainfall data obtained from SRS A-Area.

[‡]Yearly rainfall totals: 738.24 mm in 2000; 878.6 mm in 2001; 820.3 in 2002; and 1221.3 mm for 50 year average.

All control bays responded to the drought conditions with post restoration hydroperiods that were lower than those exhibited prior to treatment implementation in the restored bays. This is interesting given that the 2000 total rainfall was actually the lowest of the three years studied (Table 2). This response is likely due to timing and number of precipitation events. Water levels in the bays were high at the beginning of 2000, due to a wet period at the end of 1999. In 2001 and 2002 a few large events occurred during summer months when the control bays were dry and evapotranspiration was at its highest. As such, a period of extended ponding from the events was not observed. The increased hydroperiod in the treatment bays; however, was most likely the result of changes to the water budget via tree removal and subsequent lowering of water demand in these systems via transpiration. Similar findings pertaining to the role of forest harvesting on wetland hydrology have been noted elsewhere (Sun et al., 2000). One study indicated that the water table rise associated with harvesting is most expressed during periods when the water tables were low (Riekerk, 1989).

Given the wide variation in hydroperiod exhibited by both treatment and control bays, analyses were performed to determine what influence, if any, soils had on hydrology in these systems. Just as spatial relationships within wetland soils show differences due to parent material, elevation, frequency of flooding, vegetation, pedogenic effects, and hydrology (Johnston et al., 1984; Hayati and Proctor, 1990; Reese and Moorhead, 1996; Stolt et al., 2001), we would also expect differences among wetlands of a similar type. Stepwise multiple linear regression analyses were employed to determine relationships explaining pre-restoration hydroperiod differences between the bays (treatment and control) and surface soil properties. This approach was selected because the effects of varying wetness distributions between the sites are likely to be most expressed at the surface layer. In addition, a quick method to evaluate hydrologic conditions without a long-term monitoring commitment would be beneficial. Among the various combinations of variables, it was found that the best single independent soil variable in predicting hydroperiod was exchangeable acidity (EA) (Table 3). The best two variable model was EA and total N, which was significant at the 0.05 level. The best three variable model was EA, total N and total C.

Table 3. Multiple linear regression relationships from stepwise analysis between bay hydroperiod (Y) and surface soil exchangeable acidity, total nitrogen and total carbon.

Equation	R^2 value	F Value	Pr > F
(a) $Y = 0.96 - 0.08\ EA^{\dagger}$	0.36	2.38	0.12
(b) $Y = 1.41 – 0.19\ EA + 0.76\ N^{\dagger}$	0.51	4.13	0.05
(c) $Y = 1.24 – 0.15\ EA – 0.06\ C^{\dagger} + 1.18\ N$	0.69	3.17	0.10

†EA = exchangeable acidity (cmol kg^{-1}); N= total nitrogen (%); C = total carbon (%)

Linear regression analyses were employed to establish relationships between average hydroperiod for the three years examined and soil properties within the entire profile of the control bays. DeSteven and Toner (1997) described a relationship between bay vegetation and depth to clay and suggested that a similar relationship may exist between hydroperiod and depth to clay. When plotted, a moderate relationship ($r^2 = 0.54$; $p = 0.16$) was observed for these sites (Figure 1). Upon further analyses, a strong correlation was discovered between the clay content in the Bt horizon and hydroperiod ($r^2 = 0.90$; $p = 0.01$). The equation for the line is: Hydroperiod = 44.37(%clay content in Bt-horizon) + 20.20. Using this regression line, pre-restoration hydroperiod and % clay in the Bt data for the treatment bays was plotted to evaluate the hydrologic status of these sites. The model showed four bays (gray circles: bays 5, 124, 131, and 5016) that were wetter than would be predicted by the regression from the controls, while the remaining twelve were at the predicted level or drier (Figure 2). As such, results suggest that the four "wet" bays may not have been suitable for hydrologic restoration.

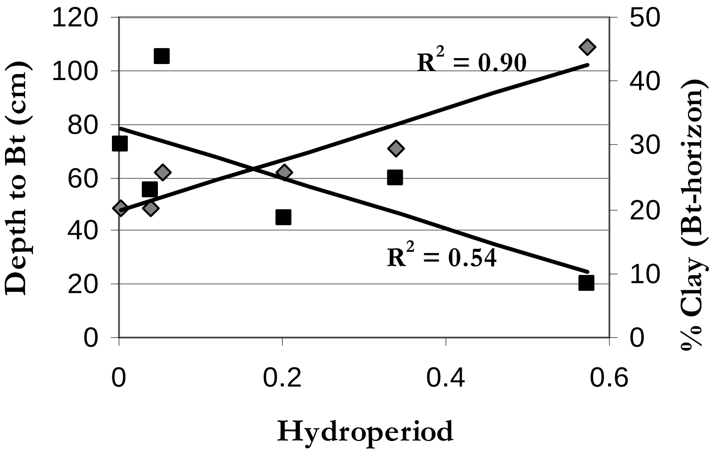

Figure 1. Influence of depth to clay and clay content in the Bt-horizon on average hydroperiod in unrestored control Carolina bays on the Savannah River Site, SC.

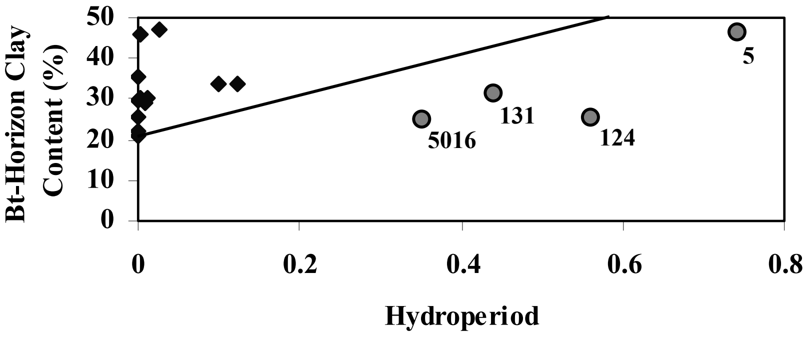

Figure 2. Evaluation of clay content in the Bt-horizon versus hydroperiod in pre-restoration treatment (drained) Carolina bays. The straight line is the line of best fit for the relationship developed for control bays. Points above the line (diamonds) were drier than the control and those below (circles) were wetter.

CONCLUSIONS

This study revealed that soil physicochemical properties could be utilized to predict Carolina bay hydroperiod and to evaluate the suitability of a bay for hydrologic restoration. Multiple linear regression analyses revealed that the chemical properties of bay surface soil samples are influenced by the variability in hydrology that these sites exhibit. Parameters that are sensitive to soil redox change or flooding, such as EA, total N and C, were found to be good indicators of hydroperiod in our sites. As such, one may evaluate the hydrologic status of a site without the long-term cost of monitoring. Regression analysis of physical parameters from the entire soil profile also revealed a significant relationship between hydroperiod and clay content in the Bt horizon. The relationship was utilized to predict hydrologic response using pre-restoration hydroperiod data. The model accurately identified sites that did not need hydrologic restoration (too wet). Subsequently, the model was employed to examine hydroperiod change after restoration and it effectively showed sites that appeared to respond well to the restoration activities. The number of disturbed Carolina bays in the southeast US could be in the tens of thousands (Sharitz, 2003), given these conditions, soil physicochemical characterizations appear to be an important and cost-efficient step in assessment procedures used to determine restoration suitability.

Acknowledgements

This work was funded by the U.S. Department of Energy-Savannah River Operations Office through the U.S. Forest Service Savannah River (Financial Assistance Award DE-IA09-00SR22188). Additional support was provided by the U.S. Forest Service Center for Forested Wetlands Research and the UGA Savannah River Ecology Laboratory.

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