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Prescribed Fire's Impact on Water Quality of Depressional Wetlands in Southwestern Georgia

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ABSTRACT.—Depressional wetlands are a natural feature of the longleaf pine-wiregrass ecosystem on the southeastern Coastal Plain. Fire is an essential part of the longleaf pine forest with prescribed burns occurring at 1–3 y intervals. In 2000 and 2001 we sampled wetlands whose surrounding uplands had been burned and reference wetlands (*i.e.*, no fire) to determine the short-term changes (<1 mo) in surface water quality. In 2000 pH, alkalinity and dissolved inorganic carbon (DIC) were higher in burned wetlands than reference sites based on ranked ANOVA. In 2001 dissolved organic carbon (DOC) and NH_4-N were higher in burned wetlands than reference ones. Differences between years suggest that field conditions are very important in determining fire's affect on water quality. To clarify our findings we conducted a laboratory experiment where we looked at changes in water quality when exposed to material (wiregrass, dead pine needles and soil) that had undergone simulated fire (muffle furnace at 340 C for 1 h). Results indicated that water exposed to burned soil had elevated pH, alkalinity, DOC, NH_4-N and soluble reactive phosphorus (SRP) compared to unburned soil. Burned wiregrass and pine needles had lower DOC and DIC levels compared to unburned material, but burned wiregrass had higher NH_4-N and SRP concentrations than the unburned treatment. Overall our results suggest that the linkage of fire and water quality of wetlands is through fire's effect on soils rather than vegetation.

INTRODUCTION

Fire is often instrumental in managing forest ecosystems (Frost, 1995; Carignan *et al.*, 2000; Engstrom *et al.*, 2001). Numerous studies have suggested fires can alter the water quality of aquatic systems by causing varying responses in sediment, turbidity, temperature, nitrogen, phosphorus and cation levels (Tiedemann *et al.*, 1979; Walbridge and Richardson, 1991). Much research has looked at fire's effect on water quality of streams (*see* Tiedemann *et al.*, 1979; Richter *et al.*, 1982), but less has looked at fire's impact on water chemistry of wetlands (Carignan *et al.*, 2000; Scrimgeour *et al.*, 2001). In the southeast United States, depressional wetlands show evidence of past fire that probably occurred on an irregular basis during droughts (Lynch *et al.*, 1986). It is known that fire can alter and direct vegetation composition (Cypert, 1961; Frost, 1995; Kirkman, 1995), but fire's affect on material subsidies into depressional wetlands is not well understood.

In boreal subartic lakes, wildfires have been found to increase soluble reactive phosphorus (SRP) and dissolved inorganic nitrogen (*i.e.*, $NO_2 + NO_3 + NH_4^+$) levels resulting in increased benthic macroinvertebrate biomass (Scrimgeour *et al.*, 2001). In a North Carolina Coastal Plain pocosin, fire increased concentrations of Mg, K, PO_4-P, NH_4-N and NO_3-N in peat (Wilbur and Christensen, 1983). In the Florida Everglades and a Florida cypress stand algal blooms occurred following wildfires suggesting nutrient additions (Odum *et al.*, 1975; Tiedemann *et al.*, 1979).

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In southeastern United States, fire is required for the management of longleaf pine (*Pinus palustis*) forests. It prevents the invasion of hardwood species and is also instrumental in releasing nutrients that otherwise are tied up in understory plants. In many cases, wiregrass (*Aristida* spp.) is the dominant understory plant that carries fire across the landscape (Engstrom *et al.*, 2001). Historically, fires were initiated by lightning and Native Americans during the growing season (summer). Present management practices prescribe fires on a 1–3 y rotational basis primarily during dormant seasons (March–April).

Within the longleaf pine forest located on the Dougherty Plain of southwestern Georgia, limesink depressional wetlands, also called seasonally-ponded isolated wetlands, are a common feature on the landscape (Lynch *et al.*, 1986). Depressional wetlands are isolated from rivers and streams. They are shallow basins occupying the center of small depressions in the landscape that typically flood in late winter or early spring by precipitation and runoff from the surrounding catchment area. Flooding typically occurs when prescribed fires are first initiated.

Previous studies have indicated that primary productivity in these wetlands is nutrient limited (Watt and Golladay, 1999; Craft and Casey, 2000; Battle and Golladay, 2001a), so fires in the upland may be instrumental in providing a nutrient pulse that could serve to enhance the productivity of these wetlands. The amount of nutrients transported into wetlands after a fire is presumably dependant on several factors such as nutrient solubility, rainfall amount, timing of rain after the fire, catchment area of the wetland, when the burn occurred (*i.e.*, summer versus winter), intensity of the burn (*i.e.*, hot versus cool fire) and severity of the burn (*i.e.*, fuel consumption). The objectives of this study were to: (1) compare water quality of several depressional wetlands whose uplands had been burned to reference wetlands (*i.e.*, no fire); and (2) relate results to a laboratory experiment where burned plant and soil matter was exposed to water.

STUDY SITE

The study occurred in southwestern Georgia at the Ichauway Reserve, which is the location of the J. W. Jones Ecological Research Center in Baker County, Newton. Ichauway Reserve is an 11,600 ha longleaf pine-wiregrass ecosystem that is situated on the Dougherty Plain, a mantled karst landscape. Elevation on the Reserve ranges from 15 m to 91 m above sea level. This area is formed of three geologic units; the surface residuum composed of porous sand and clay (1–40 m), followed by the Ocala limestone that contains the upper Floridan aquifer (1–100 m) and lastly the Lisbon Formation, a dense confining limestone layer. Wetlands are formed by dissolution of Ocala limestone and collapse of overlying residuum (Hayes *et al.*, 1983). It is believed that basins gradually become sealed with clay allowing them to hold water (Engstrom *et al.*, 2001). These wetlands tend to flood during late February and dry during early July. Wetlands are shallow, irregularly shaped and vary in size from <1 ha to >20 ha, with the average wetland for the study being 3 ha.

In southwestern Georgia there are three types of depressional wetlands that are distinguished based on soils and vegetation: grass-sedge marshes, cypress-savannas and cypress-gum swamps (Kirkman *et al.*, 2000). Grass-sedge marshes have loamy-sand soils and a dense ground-flora dominated by panic grasses (*Panicum* spp.) and cutgrass (*Leersia hexandra* Sw.). Cypress savannas have clayey soils and are characterized by a sparse overstory canopy of pond cypress (*Taxodium ascendens* Brongn.), an interspersed ground-flora composed mainly of panic grasses and broomsedge (*Andropogon virginicus* L.). Cypress-gum swamps have organic soils, an overstory canopy dominated by pond cypress and swamp tupelo (*Nyssa biflora* Walt.), and sparse ground-flora and midstory canopy.

METHODS

Field study.—In 2000 and 2001 we sampled water chemistry of wetlands in reference sites (*i.e.*, no fire) and wetlands whose adjacent uplands had been burned, hereafter referred to as burned wetlands. Wetlands were one of the following types: marsh, savanna or swamp (Table 1). Preburn samples were taken before the fire and the first postburn sample was taken after the fire but before any significant rainfall (<4 cm). Other postburn samples were taken after subsequent rainfalls and dates were determined by rainfall timing and amounts. There were six reference wetlands and five burned wetlands in 2000 and there were six reference and seven burned sites in 2001 (Table 1). In 2000 preburn samples were taken 22 Feb., catchment areas were burned 11 Mar. and postburn samples were taken 17 Mar., 20 Mar. and 4 Apr. (Fig. 1). In 2001 preburn sampling occurred on 21 Mar., sites were burned 23 Mar. and postburn samples were collected 28 Mar., 30 Mar. and 2 Apr. Rainfall amounts (Georgia AEMN, 2001) and water levels in wetlands, measured with stationary staff gauges, are shown in Figure 2.

In 2000 weather conditions on the day of the prescribed fire were the following: air temperature 18 C, wind speed 24 km/h and relative humidity 30%. In 2001 conditions on the burn day were the following: air temperature 22 C, wind speed 16 km/h and relative humidity 28%. Weather conditions were based on an average afternoon low and high reported by the local weather station. Weather, time of year and low fuel accumulation in sites were important factors in creating low intensity fires. During March in southwestern Georgia the Keetch-Byram Drought Index is typically below 200, indicating high soil and fuel moisture (J. Stober, Jones Research Center, pers. comm.).

Sampling of surface waters consisted of filling 1-liter bottles 2–4 m from the edge of the wetland at three distant locations around the wetland. In the same areas we measured dissolved oxygen and temperature (YSI Model 55, Yellow Springs, Ohio). Samples were transported back to the lab on ice and then filtered (Gelman A/E, GFF, 1-μm pore size). Water chemistry was determined according to standard procedures (*see* Battle and Golladay, 2001b). We measured dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) with a Shimadzu TOC-5050 analyzer. We determined NH_4-N, NO_3-N and soluble reactive phosphorus (SRP) with a Lachat Quikchem 8000 flow-injection colorimetric method (Lachat Instruments, 1998). Using unfiltered water, alkalinity and pH were assessed with a Mettler DL12 tritrator.

Laboratory study.—The purpose of the laboratory study was to examine how water quality differed with exposure to burned and unburned wiregrass (*Aristida beyrichiana*), abscised longleaf pine needles and upland soil (Kutiel and Shaviv, 1992). Plant material and soil (top 2-cm) were collected from an area adjacent to an unburned wetland on 11 Mar. 2002. Three separate experiments were conducted, one for each material, using twelve 500-ml flasks that had been heated in a furnace (1 h, 500 C). Samples were prepared by weighing to the nearest 0.01 g, 2.5 g for each plant material and 5 g of soil. There were four flasks of unburned material, four flasks of burned material and four flasks of no material (control). To simulate burning, material was placed at 340 C for 1 h and then allowed to cool. The temperature of 340 C was based on an average value (n = 42) measured at the soil surface during prescribed fires during 1994 on the Ichauway Reserve (C. Wilson, Jones Research Center, pers. comm.). Following cooling, 500-ml of ultrapure water (Picopure, Hydro Services and Supplies, Inc, Research Triangle Park, NC) was added to each flask. After 24 h samples were analyzed for water chemistry as previously described.

Data analysis.—Initially, the average concentration for the water quality variables was determined by wetland and date. For the field experiment water quality variables for the

TABLE 1.—Study treatment, wetland type and number of wetlands sampled. Wetland type is based on soils and vegetation (Kirkman *et al.*, 2000)

Year	Treatment	Wetland type	# of wetlands
2000	Reference	Marsh	3
		Savanna	2
		Swamp	1
	Burned	Marsh	3
		Savanna	1
		Swamp	1
2001	Reference	Marsh	4
		Savanna	2
	Burned	Marsh	3
		Savanna	4

preburn samples were tested for normal distribution and log transformed if needed. Then, a *t*-test was used to compare preburn samples to ensure there was no differences in water quality between reference and burned wetlands before the fire ($\alpha = 0.05$). To examine the effects of prescribed fire, ANOVA was used to determine if differences in water chemistry existed between years, treatments (*i.e.*, reference vs. burned) and their interaction. ANOVA indicated that water chemistry variables differed significantly by year ($P > 0.05$), therefore, each year was analyzed separately. To do this, postburn samples from the three sample dates were pooled and reference versus burned sites were compared using ranked ANOVA. Tukey's Significant Difference Test was performed on the rank-transformed data and results were then represented by boxplots (Helsel and Hirsch, 1992). For the laboratory experiment, water chemistry was compared between unburned and burned material (*i.e.*, wiregrass, pine needles and soil) using a *t*-test.

RESULTS

In 2000 there was a drought, wetlands were not fully inundated and fires burned across a large percentage of the wetland basins. In 2001 wetlands were more inundated than the previous year (Fig. 1) and fires burned only to the outer edges of wetlands. The severity of the prescribed fires was characterized as lightly to moderately burned, *i.e.*, litter and duff layer were scorched but not always over the entire depth and underlying mineral soil was not visibly scorched (Wells *et al.*, 1979). There were no significant differences in water quality of preburn samples between reference and burned wetlands for either year ($P > 0.05$). For postburn samples in 2000 pH, alkalinity and DIC were significantly different between treatments, with all variables being higher in burned sites than reference wetlands (Fig. 2). For postburn samples in 2001 DOC and NH_4-N were significantly higher in the burned wetlands than reference sites (Fig. 2).

Laboratory results indicated that combusted wiregrass, pine needles and soil altered water chemistry (Table 2). Water quality in flasks containing burned pine needles and wiregrass showed lower concentrations of DOC and DIC compared to the unburned treatments. Additionally, burned wiregrass also showed increased concentrations of NH_4-N and SRP compared to unburned wiregrass. Water exposed to heated soil had elevated pH, alkalinity, DOC, NH_4-N and SRP compared to reference soil. There were no differences in NO_3-N concentrations between burned and unburned for either of the plant materials or soil (Table 2).

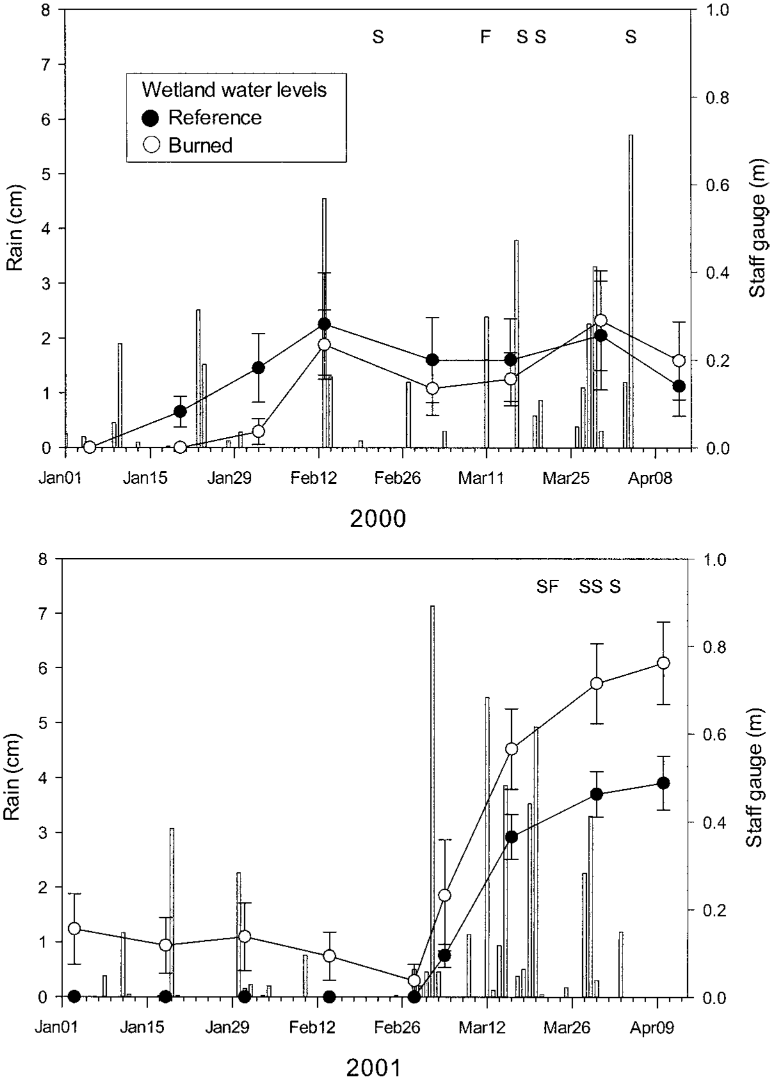

FIG. 1.—Rain amounts during 2000 and 2001 study periods shown as bars. Water levels in reference and burned wetlands designated by lines and error bars indicate SE. Letters indicate when sampling (S) and fire (F) occurred

DISCUSSION

No differences in water quality were found between reference and burned wetlands for preburn samples indicating that changes in water quality were due to fire in the surrounding uplands. Earlier work has indicated that during the initial months of flooding water quality is similar among the three wetlands types (*i.e.*, marshes, savannas and swamps) most likely reflecting rainfall chemistry (Battle and Golladay, 2001b). For the two study years, the different effects of fire on water quality in all probability indicate differing field conditions.

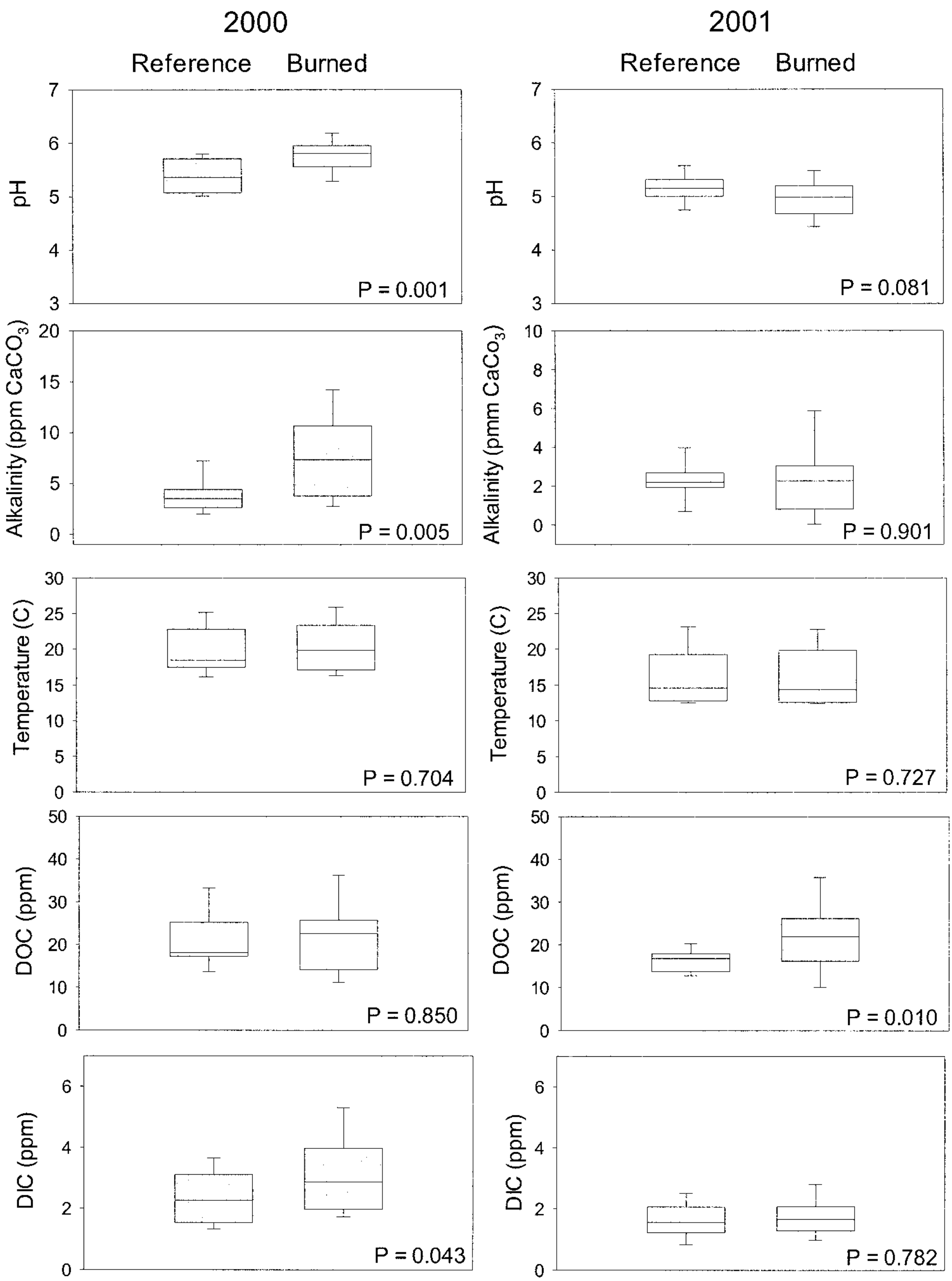

FIG. 2.—Water chemistry during 2000 and 2001 studies. Box-plots of variables comparing reference and burned treatments for each year. Significant variables shown as grey boxes ($P < 0.05$) and non-significant variables shown as white boxes. Box-plots represent median and 10^{th}, 25^{th}, 75^{th} and 90^{th} percentiles. P values are based on ranked ANOVA

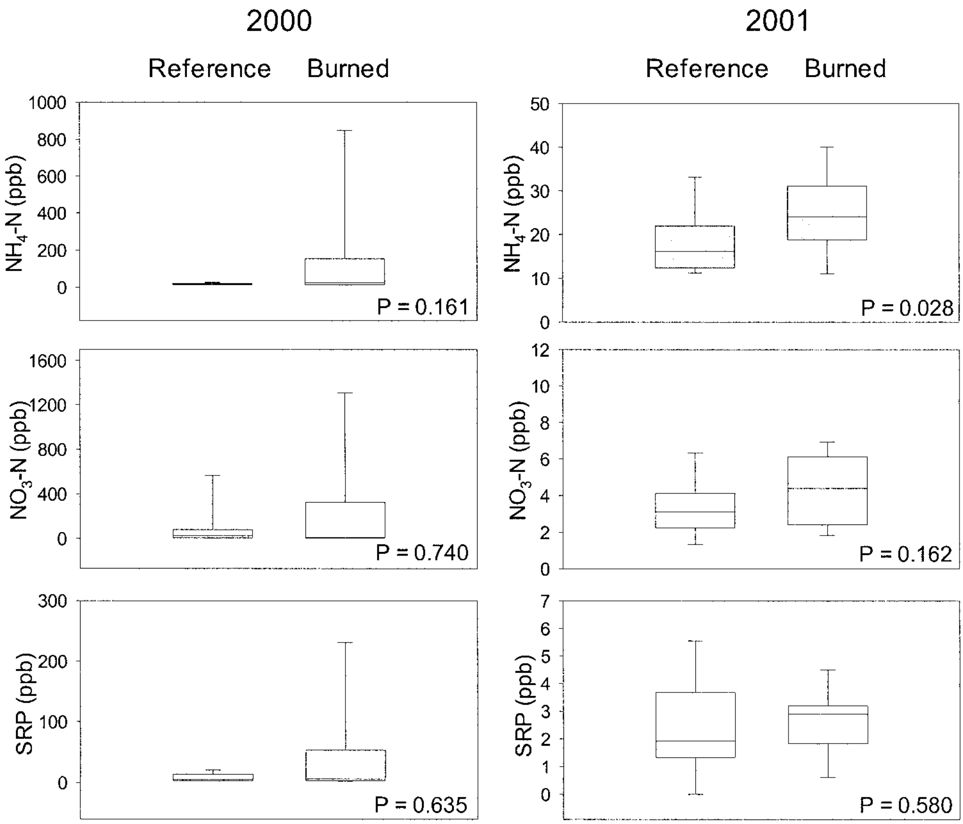

FIG. 2.—Continued

In 2000 there were more extensive fires that encroached into the wetlands compared to 2001 when wetlands were more inundated and there was more rainfall following the fire. Intensity of a burn is important in determining subsidies released (DeBano *et al.*, 1998).

In 2000 water chemistry in burned wetlands had higher pH, alkalinity and DIC. The laboratory study indicated that burning soil increased pH and alkalinity, but that burning wiregrass and pine needles did not alter pH (Table 2). In addition, alkalinity actually decreased when wiregrass was exposed to heat. Therefore the increases in pH and alkalinity observed in 2000 appear to result from fires burning the surface soils resulting in carbonates and hydroxides leaching from the ash. Increases in soil pH after fires have been attributed to ash accretion since ash is dominated by carbonates of alkaline and alkaline earth metals (Ahlgren and Ahlgren, 1960; Kutiel and Shaviv, 1992). The response depends on the amount of ash and buffering capacity of the soil (Ahlgren and Ahlgren, 1960) and water. The elevated DIC levels we measured can be attributed to increased bicarbonate levels that occur when carbon dioxide, a by-product of combustion, dissolves in water. Many stream studies have reported that fire increases bicarbonate in soil solution and in streamflow (*see* Tiedemann *et al.*, 1979).

In 2000, although there was no significant difference between treatments for NO_3-N and SRP there were two burned wetlands, a savanna and a marsh, which had very high levels of

TABLE 2.—Results of laboratory experiment comparing the difference of water quality for unburned and simulated burned material of wiregrass, pine needles and soil. Listed are the means with standard deviations in parentheses. Asterisks indicate unburned and burned material were significantly different based on a *t*-test (* $P < 0.05$, ** $P < 0.005$)

	Wiregrass			Pine needles			Soil		
	Unburned	Burned		Unburned	Burned		Unburned	Burned	
pH	4.99 (0.27)	4.69 (0.12)		4.89 (0.23)	4.87 (0.05)		5.49 (0.04)	5.89 (0.02)	**
Alkalinity (ppm $CaCO_3$)	1.36 (0.72)	0.28 (0.33)	*	0.54 (0.25)	0.44 (0.09)		1.48 (0.30)	4.29 (0.69)	**
Apparent color (PtCo)	10.75 (1.89)	2.00 (0.00)	**	5.00 (0.82)	0.50 (0.58)	**	86.00 (9.90)	7.00 (5.35)	**
DOC (ppm)	5.51 (1.36)	0.98 (0.30)	**	2.78 (0.81)	0.28 (0.13)	*	0.96 (0.18)	4.83 (1.11)	*
DIC (ppm)	2.28 (0.85)	0.00 (0.00)	*	1.01 (0.30)	0.00 (0.01)	*	0.31 (0.06)	0.28 (0.08)	
NH_4-N (ppb)	0.00 (0.00)	12.28 (2.02)	**	0.00 (0.00)	4.91 (3.82)		5.40 (2.29)	101.51 (11.70)	**
NO_3-N (ppb)	0.00 (0.00)	0.73 (1.46)		0.00 (0.00)	0.00 (0.00)		1.25 (0.88)	0.31 (0.61)	
SRP (ppb)	8.88 (12.00)	76.21 (18.54)	**	3.53 (2.58)	11.00 (10.59)		4.34 (0.70)	65.50 (7.67)	**

NO_3-N (>350 ppb above reference sites) and SRP (>100 ppb above reference sites). These were also the two wetlands that had the largest area of their basin burned, >50%. Wilbur and Christensen (1983) found that PO_4-P and NO_3-N were noticeably more variable spatially in the burned peat-layer of an ombrotrophic shrub-bog. Depressional wetlands could also have variability in nutrient concentrations between their basins and uplands due to variation in vegetation and soils (Kirkman *et al.*, 1998). Also, if the fire occurs within the wetland basin, nutrients have a shorter distance to travel before entering water.

In 2001 DOC and NH_4-N levels were higher in the burned wetlands indicating significant rainfall amounts and timing of rainfall after the fire provided an influx of material into the wetlands. High DOC levels may be the result of sediment runoff. Many stream studies have shown increases in sediment transport following fires (*see* Tiedemann *et al.*, 1979); however, because uplands surrounding the wetlands are low, gradient increases in DOC are more likely due to the effects of incomplete combustion of soil organic matter settling as ash in the wetland (Lynch *et al.*, 1986). In southwestern Georgia, soil permeability and flat topography cause rainfall to infiltrate the soil and enter the wetlands from subsurface flow paths (Hayes *et al.*, 1983). There has been little research examining the impact of ash on water quality, but analysis of ash from a 1994 prescribed fire on Ichauway Reserve indicate that total carbon makes up to 28.7 % (±8.2 SD) of ash content (n = 87; C. Wilson, pers. comm.).

Elevated DOC and NH_4-N measured in the burned wetlands during 2001 were consistent with the laboratory study of burned soils. NH_4-N is released with the combustion of organic matter and is formed by the decomposition of secondary amide groups and amino acids (*see* DeBano *et al.*, 1998). It has been shown that above 100 C, secondary amide groups decompose in protein-like components of a clay-organic soil to yield NH_4-N (Russell *et al.*, 1974). Wilbur and Christensen (1983) also noted increases in availability of NH_4-N, NO_3-N and PO_4-P in pocosin soils after a fire and suggested increased nutrient availability may be due to ash addition, reduced plant uptake or changes in rates of mineralization.

The field and laboratory studies had different SRP dynamics. The laboratory experiment suggested that large amounts of SRP are released from soil and wiregrass following a burn, but we observed no changes in the field data, even though several field studies have found that fire increased SRP levels (Wilbur and Christensen, 1983; Scrimgeour *et al.*, 2001). Differences in water quality concentrations between the laboratory and field study may be the result of one fixed temperature in the laboratory versus a wide range of temperatures in the field. Potentially, laboratory material may have been burned at a higher temperature than field material and, therefore, more complete combustion occurred. Stark (1977) found total phosphate-P was higher with hotter fires (>300 C at the soil surface) vs. cooler burns (200–300 C). Another reason for the lack of measurable change in SRP in the field may be due to its quick uptake in the uplands by microbes and the regeneration of forest floor plant communities (Engstrom *et al.*, 2001). In addition, SRP is naturally bound to soil and does not move readily in groundwater. Therefore, even if SRP is released upon burning, its reactivity makes it is less likely to be transported into the wetlands. SRP that does enter the wetlands may be rapidly assimilated by algae and bacteria since primary production and decomposition in wetlands has been reported as P-limited (Watt and Golladay, 1999; Battle and Golladay, 2001a).

Historically there were probably more catastrophic fires than present day prescribed fires. Loss of catastrophic fire results in fewer shifts in vegetation and potential decreases in productivity (Frost, 1995) because lower intensity fires do not consume extensive layers of litter. Studies have suggested less dramatic changes in water quality of streams for prescribed fires vs. wildfires (*see* DeBano *et al.*, 1998). Richter *et al.* (1982) found that prescribed burns did not alter water quality of streams located on the Coastal Plain in South Carolina. Our study indicated that even low intensity prescribed fires are capable of altering water quality of wetlands in southwestern Georgia and that it is the scorching of soils that is most responsible for changes in water chemistry.

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