Effects of Burn Temperature on Ash Nutrient Forms and Availability from Cattail (*Typha domingensis*) and Sawgrass (*Cladium jamaicense*) in the Florida Everglades

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Plant ash derived from fire plays an important role in nutrient balance and cycling in ecosystems. Factors that determine the composition and availability of ash nutrients include fire intensity (burn temperature and duration), plant species, habitat nutrient enrichment, and leaf type (live or dead leaf). We used laboratory simulation methods to evaluate temperature effects on nutrient composition and metals in the residual ash of sawgrass (*Cladium jamaicense*) and cattail (*Typha domingensis*), particularly on post-fire phosphorus (P) availability in plant ash. Live and dead leaf samples were collected from Water Conservation Area 2A in the northern Everglades along a soil P gradient, where prescribed fire may be used to accelerate recovery of this unique ecosystem. Significant decreases in total carbon and total nitrogen were detected with increasing fire temperature. Organic matter combustion was nearly complete at temperatures ≥450°C. HCl-extractable P (average, 50% of total P in the ash) and NH_4Cl-extractable P (average, 33% of total P in the ash) were the predominant P fractions for laboratory-burned ash. Although a low-intensity fire could induce an elevation of P availability, an intense fire generally resulted in decreased water-soluble P. Significant differences in nutrient compositions were observed between species, habitat nutrient status, and leaf types. More labile inorganic P remained in sawgrass ash than in cattail ash; hence, sawgrass ash has a greater potential to release available P than cattail. Fire intensity affected plant ash nutrient composition, particularly P availability, and the effects varied with plant species and leaf type. Therefore, it is important to consider fire intensity and vegetation community when using a prescribed fire for ecosystem management.

Wild and prescribed fires play an important role in nutrient cycling within ecosystems (Wan et al., 2001). During a fire, elements contained in vegetation or surface soil can be transferred into the atmosphere or to adjacent areas via nonparticulate (volatilization) and/or particulate (ash) pathways (Raison et al., 1985). Nutrient loss from the burned site is most likely through volatilization and results in atmospheric pollution (Cachier et al., 1995; McNaughton et al., 1998; Liu et al., 2000). Nutrients in ash can be deposited on-site or redistributed to adjacent areas via wind, rainfall, erosion, runoff, and leaching. This may have a significant impact on the soil nutrient status and water quality (Hauer and Spencer, 1998; Thomas et al., 1999; Townsend and Douglas, 2000; Badía and Martí, 2003). The number of storms per year; temperature extremes; and the length, intensity, and amount of precipitation have been found to influence nutrient releases from ash (Stark, 1977). Increased post-fire nutrient concentrations in soil and water have been observed (Ilstedt et al., 2003; Úbeda et al., 2005; Murphy et al., 2006b). Badía and Martí (2003) found that the addition of ash increased soil organic matter content, carbon (C) and nitrogen (N) ratio, pH, and nutrient availability. Spencer et al. (2003) documented increased P and N levels in streams post-fire resulting from the aerial deposition of smoke and ash. These increased 5- to 60-fold above the background levels. However, enhanced erosion after fire may result in a loss of N, exchangeable potassium (K), and available P in soil (Thomas et al., 1999). A study conducted by Smith et al. (2001) in a degraded Everglades wetland found that a peat fire resulted in loss of organic P and increases in inorganic P. Such an increase of inorganic P availability could encourage the growth of invasive plant species (e.g., *Typha domingensis*) in the Everglades (Smith and Newman, 2001). Ulery et al. (1993) pointed out that wood-ash can increase the pH of

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Published in J. Environ. Qual. 38:451–464 (2009).
doi:10.2134/jeq2008.0126
Received 13 Mar. 2008.
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Abbreviations: DDI water, double deionized water; HCD, dead leaf of cattail from highly impacted zone; HCL, live leaf of cattail from highly impacted zone; H zone, highly impacted zone; MCD, dead leaf of cattail from moderately impacted zone; MCL, live leaf of cattail from moderately impacted zone; MSD, dead leaf of sawgrass from moderately impacted zone; MSL, live leaf of sawgrass from moderately impacted zone; M zone, moderately impacted zone; RCD, dead leaf of cattail from reference zone; RCL, live leaf of cattail from reference zone; RSD, dead leaf of sawgrass from reference zone; RSL, live leaf of sawgrass from reference zone; R zone, reference zone; WCA 2A, Water Conservation Area 2A.

underlying soils as much as three pH units due to large amounts of basic cations in ash. Promotion of clay dispersion by ash was also reported (Ulery et al., 1993). Therefore, understanding nutrient composition and availability in ash is essential when evaluating post-fire environmental quality.

One factor determining ash nutrient availability is fire intensity (i.e., fire temperature and duration) (Ulery et al., 1993; Certini, 2005). Elements may be volatilized or mineralized depending on their vaporization points and the fire temperatures. Nutrients become more available, volatilized and lost from the site, or less available due to binding to basic cations. At temperatures of 400 to 500°C, organic compounds are degraded and oxidized completely, and most carbon, hydrogen, oxygen, nitrogen, and sulfur are in the gas phase due to their relatively low vaporization temperatures (Gray and Dighton, 2006). Although elemental P and metals have relatively high vaporization temperatures (e.g., 774°C for P and K and 1484 for calcium [Ca]), these elements may be bound within organic or inorganic compounds in biological materials and have lower vaporization points compared with their inorganic elemental forms. Raison et al. (1985) reported gaseous loss of P as P_4O_{10} (oxygen excess) and P_4O_6 (oxygen limiting) in the field. These volatilized P compounds may form phosphoric acids in smoke and eventually return to the ground. However, in a laboratory simulation, all of the P remained in the solid phase and accumulated in ash due to its relatively high vaporization temperature and limited air movement (Gray and Dighton, 2006). Furthermore, inorganic P tends to bind with basic oxides in the ash with increasing temperature, forming insoluble P and thus decreasing the P availability (Ulery et al., 1993; Gray and Dighton, 2006). Adsorption of P to newly exposed or newly created iron (Fe) and aluminum (Al) oxyhydroxy soil mineral sites was previously reported (Blank et al., 1994; Murphy et al., 2006a). Basic cations (e.g., K, magnesium [Mg], and Ca) can also accumulate in ash and often result in the elevation of surface soil pH (Dikici and Yilmaz, 2006; Murphy et al., 2006a).

Other factors, including plant species, habitat nutrient availability, and live/dead ratio of aboveground biomass, can affect the nutrient availability of ash (Debano and Conrad, 1978; Gray and Dighton, 2006). Responses of plant nutrients to fire vary among species, resulting in different nutrient retention and availability in ash. This can be attributed to the differences in the structural and metabolic compounds among plants (Gray and Dighton, 2006). For example, among the three species studied, black huckleberry leaf litter that had the highest nutrient content yielded the most available nutrients after burning. Plants growing along a nutrient gradient showed variation of nutrient content within species (Miao and Sklar, 1998), which could affect post-fire nutrient allocation. However, no previous report is available to compare the effects of fire temperature on plant ash nutrient composition of intra-species response of plants growing along a nutrient gradient. In general, dead leaves exhibited lower nutrient concentrations than live leaves as a result of nutrient retranslocation during leaf senescence (Miao, 2004). Debano and Conrad (1978) observed that nutrients (e.g., N, P, K, Mg, and Ca) in live plants and litter were made available by fire in proportion to the amount in plant tissue before burning.

As one of the largest and most unique wetlands in the world, the Florida Everglades, occupying around 6200 km^2 in area and rich in wildlife, has been influenced by anthropogenic activities. This has led to significant ecosystem changes in geographic extent, environmentally driven factors (e.g., hydrology and fire), biotic diversity, and nutrient biogeochemical cycling (Noe et al., 2001). Particularly, P enrichment is one of the dominant impacts because this freshwater wetland ecosystem is highly sensitive to even small shifts in P concentrations (Noe and Childers, 2007; Noe et al., 2007). Thousands of hectares of historically sawgrass (*Cladium jamaicense*) dominant, oligotrophic Everglades have been replaced by cattail (*Typha domingensis*), which is characteristic of P-enriched habitats (Miao and Sklar, 1998). To accelerate the ecosystem recovery process, active management of the existing cattail marsh, including prescribed fires, is considered a potential tool for Everglades restoration. Therefore, it is essential to evaluate ash nutrient compositions and availability for assessing fire effects on nutrient availability in the Everglades.

There is limited information available regarding plant ash nutrient form and availability (Debano and Conrad, 1978; Badía and Martí, 2003). Most of the previous studies focused on the post-fire nutrient status of the soil and water column (Ilstedt et al., 2003; Spencer et al., 2003; Stephens et al., 2004; Yermakov and Rothstein, 2006). Phosphorus fractions in plant ash remain unknown for the Florida Everglades, although this is an essential method to assess post-fire P availability. With P fraction information, it is possible to quantify post-fire P availability in detail and thus initiate a better understanding of how fire affects ecosystem structure and associated biogeochemical processes. This is particularly true for the Everglades ecosystem, where the role of fire in P biogeochemistry processes has not been thoroughly investigated, including the variation of P species in ash, surface water, pore water, and soil (Smith et al., 2001).

Our objectives were to determine (i) the effects of burn temperature on nutrient availability in plant ash; (ii) how the temperature effects varied within species, habitat nutrient enrichment, and leaf types; and (iii) the P fractions in ash to assist in a post-fire P availability evaluation. To the best of our knowledge, this is the first investigation of P fractionation in plant ash.

Materials and Methods

Site Description

Leaves of sawgrass (*Cladium jamaicense*) and cattail (*Typha domingensis*) were collected from Water Conservation Area 2A (WCA 2A) within the northern Everglades (Fig. 1). Sawgrass is a leafy stemmed perennial sedge and is characterized by grass-like, saw-toothed leaves and highly branched inflorescence of spikelets. Cattail is a perennial monocotyledonous flowering plant, is typically 1 to 7 m tall, and has spongy, strap-like leaves and starchy, creeping stems (rhizomes) (Miao and Sklar, 1998). Water Conservation Area 2A, occupying 442 km^2, is a historically oligotrophic wetland. Histosols are typical soil types in this area (mainly peat soil derived from decaying plant matter), with 1.3 m thickness and 85% organic matter on average. Soil Eh at 2.5 to 20 cm depth is below 100 mV and soil pH is neutral (Stober

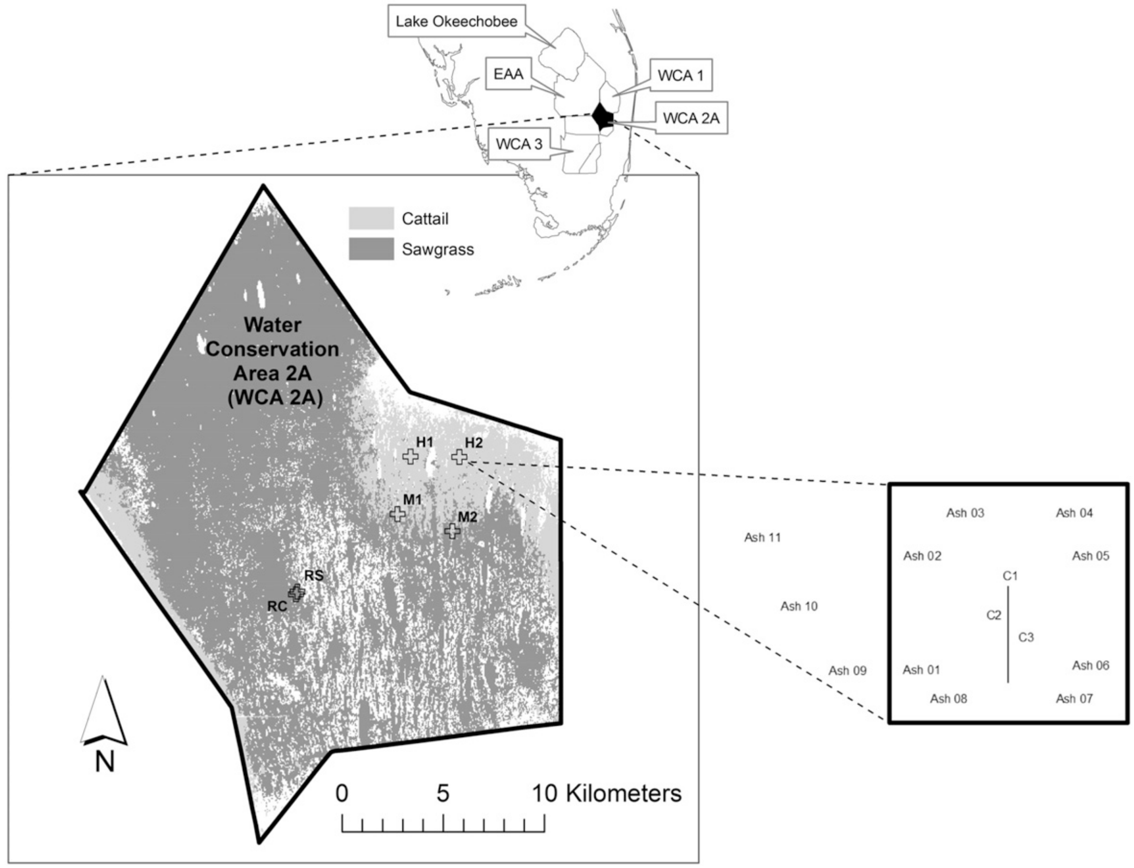

Fig. 1. Sampling location in Water Conservation Area 2A (WCA 2A), northern Everglades, South Florida. Leaf samples of cattail and sawgrass were collected from unburned H1 (highly impacted zone), M1 (moderately impacted zone), and RS (reference zone) areas, and ash samples were collected from H2 (highly impacted zone) where the prescribed fire was made in July 2006.

et al., 1998). Water Conservation Area 2A has suffered significant alterations of hydrologic patterns and nutrient sources from agricultural activity and urbanization. The estimated annual average loadings of P and N were 60 metric tons and 1814 metric tons, respectively, into WCA 2A since the late 1970s (Richardson et al., 1999). In the 1990s, the annual P inputs into the WCAs almost tripled historic levels (Noe et al., 2001). Increases in soil nutrients (N, P, C, metals), especially a P gradient with the greatest P concentration in the northern boundary, have been well documented for WCA 2A (Miao and Sklar, 1998; Richardson et al., 1999; Noe et al., 2001; Noe and Childers, 2007).

Three nutrient impacted zones along a nutrient gradient from the highly P-enriched area in the north to low soil P concentrations in the south of WCA 2A were studied (Fig. 1): a highly impacted zone (H zone, 26°34′N and 80°37′W; 1000–1200 mg total P kg^{-1} soil), a moderately impacted zone (M zone, 26°32′N and 80°38′W; 600–1000 mg total P kg^{-1} soil), and a reference zone (R zone, 26°28′N and 80°42′W <500 mg total P kg^{-1} soil). Live and senescent cattail leaves were collected from all three zones, whereas live and dead sawgrass leaves were collected from the M and R zones only. Cattail ash samples were also collected from the H zone after a prescribed fire on 25 July 2006. Briefly, 22 ash collectors (30 × 40 × 6 cm aluminum pans) were installed within the highly impacted zone (H2 area; Fig. 1). Two collecting pans were installed at each within-plot sampling station with one pan just above the surface of the water but below a thick mat of senesced leaves and the second at roughly 2 m above the peat surface. The vertical locations of the collectors were offset such that the upper collector did not interfere with ash entering the lower collector. The ash was carefully brushed from the aluminum pans into wide-mouth plastic jars within a half an hour after the fire, and the samples were stored at room temperature for later nutrient analyses.

Laboratory Analyses

All plant samples collected in the field were separated into 10 subsamples based on the species, whether live or senescent, and with plots as follows: live cattail leaves from highly impacted zone (HCL), moderately impacted zone (MCL), and reference zone (RCL); dead cattail leaves from highly impacted zone (HCD), moderately impacted zone (MCD), and reference zone (RCD); live sawgrass leaves from moderately impacted zone (MSL) and reference zone (RSL); and dead sawgrass leaves from moderately impacted zone (MSD) and reference zone (RSD). Leaves were cut into approximately 0.5-cm pieces and mixed well. Water content was estimated by oven-drying each subsample at 60°C for 5 d. Nutrients, including C, N, P, and metals (Mg, Ca, K, iron [Fe], and aluminum [Al]), and pH values were determined for oven-dried and muffle furnace burned subsamples. Approximate 2 g triplicates of each subsample (field moist samples) were placed into oven-dried, pre-weighed beakers and heated to 150, 250, 350, 450, or 550°C for 2 h in a muffle furnace. Triplicates at each temperature were heated together. After cooling within a desiccator, these burned samples were reweighed to calculate mass loss and ash content and subjected to further pH and nutrient analyses using the procedures described below. Similarly, baseline nutrient levels and pH values were determined for oven-dried (60°C, 5 d) subsamples using procedures described below.

Ash and plant residue pH were measured from a 1:50 dilution with double deionized (DDI) water using an AR-60 Dual Channel pH/Conductivity meter. Total C (TC) and total N (TN) were determined using an Elemental CNS analyzer. To measure water-dissolved nutrients, including ammonia (NH_4–N), nitrite (NO_2–N), nitrate (NO_3–N), phosphate (PO_4–P), Ca^{2+}, K^+, Mg^{2+}, Fe^{2+}, and Al^{3+}, burned and oven-dried samples were extracted with 20 mL of DDI water for 2 h, followed by centrifugation (1789 × *g*, 15 min) and filtration (0.45-μm MAGNA Micron membrane). To quantify total P (TP) and total metals, oven-dried and burned samples were dry-ashed at 550°C for 4 h, dissolved in 2 mL of 6 mol L^{-1} HCl, and diluted with 18 mL of DDI water. Solutions for quantification of metals (total or water soluble) were acidified with concentrated HNO_3 (to 0.2% v/v solutions). A summary of analytical methods is presented in Table 1.

Phosphorus fractionation was conducted for fresh-white ash burned at 450 and 550°C using the procedure modified from Hieltjes and Lijklema (1980) by adding a DDI water extraction step before the NH_4Cl extraction (Fig. 2). Filtration with a 0.45-μm membrane after each extraction was preceded by centrifugation (1789 × *g*, 15 min). We selected this method because of the elevated pH in ash and because high concentrations of base cations (especially Ca) in ash were expected. Furthermore, organic P would likely be negligible because at temperatures of 400 to 500°C, organic compound degradation and carbon oxidation is nearly complete (Gray and Dighton, 2006). Thus, the method of Hieltjes and Lijklema (1980), which was primarily developed for inorganic P fractionation in calcareous sediments and adopted by previous studies (Rydin, 1996; Carlyle and Hill, 2001; Tiyapongpattana et al., 2004), can be used for plant ash P separation.

Total N, TC, TP, total metals, and P fractions were determined in the ash samples collected from the field to compare with the laboratory simulation results.

Statistical Methods

Results from oven-dried and muffle furnace burned samples were examined using the PROC GLM program (Version 9.1.2., SAS Institute Inc., Cary, NC). Analysis of variance was used to determine the main effects and interactions of each factor. Oven-dried leaf samples were grouped into 10 subsamples based on species, habitats, and leaf type (i.e., HCL, MCL, RCL, HCD, MCD, RCD, MSL, RSL, MSD, RSD) and subjected to Duncan's multiple range test to evaluate variations of baseline nutrient contents. Differences were considered significant at $p < 0.05$, $p < 0.01$, and $p < 0.001$. Main effects of temperature were further determined by Tukey's studentized range (HSD) test at $\alpha = 0.05$ due to the quantitative nature of temperature. Means were separated using Duncan's multiple range test for other categorical factors (Little, 1978).

The following piecewise equation was used to estimate the average combustion temperature during the field fire based on the laboratory simulation results (Eq. [1]):

$$f(t)=\begin{cases}\dfrac{y_1(T_1-t)+y_2(t-t_1)}{T_1-t}, & t_1\le t\le T_1;\\[2ex] \dfrac{y_2(T_2-t)+y_3(t-T_1)}{T_2-T_1}, & T_1\le t\le T_2;\\[2ex] \dfrac{y_3(t_3-t)+y_4(t-T_2)}{t_3-T_2}, & T_2\le t\le t_3.\end{cases} \qquad [1]$$

where *f*(*t*) is the nutrient concentration (i.e., the concentrations of total phosphorus [TP], TN, and TC in ash, mg g^{-1} of dry leaf material) as a function of burning temperature t (°C); t_1 and t_3 are the minimum and maximum temperatures applied in laboratory simulation (i.e., 150 and 550°C), respectively; T_1 and T_2 are the first and second breakdown points of temperature, respectively (°C); and y_1, y_2, y_3, and y_4 are the parameters determined by fitting the model with experimental data. For the TP curve, there were two segments, whereas three segments were used for the TN and TC curves. This equation was selected because it is significant for describing the responses of nutrient (TN, TC, and TP) concentration to burning temperature (for all six regressions, $0.93 < r^2 < 0.99$; $p < 0.01$).

Results

Nutrient Content in Unburned Plant

The ANOVA results indicated that pH, ash production, and most of the nutrient content in plant material significantly varied with burning temperatures, species (cattail and sawgrass), nutrient impacted zones (highly impacted, moderately impacted, and reference zones), leaf types (live or dead leaves), and/or their interactions (Table 2). Table 3 shows variations of baseline nutrient contents between species, between leaf types, and among nutrient impacted zones.

Generally, for species from the same sampling location, almost all total nutrients except TC, total Fe (TFe), and Al (TAl) showed greater levels in cattail than in sawgrass live leaf, reflecting differences in structural and metabolic compounds in the different species. Furthermore, N and P in plant leaves varied with the nutrient gradient along the sampling locations. Live leaf TN, total organic N (TON), and TP were significantly greater in cattail from the H zone than that from the M and R zones. Sawgrass from the moderately impacted zone contained significantly greater TP than sawgrass from the reference zone. For example, the average TP content was 1.18 mg g^{-1} for HCL, whereas it was 0.56 and 0.54 mg g^{-1} for MCL and RCL, respectively; 0.63 mg g^{-1} for MSL; and 0.21 mg g^{-1} for RSL (Table 3). Live leaves of cattail and sawgrass contained more TN, TON, TP, and

Table 1. Analytical methods for selected parameters with pH unit for pH, mg g^{-1} for TN and TC, and mg L^{-1} for the other parameters.

Parameters	Analytical method	Instrument	Detection limits
pH	ash:DDI water = 1:50	AR-60 pH meter (Fisher Scientific, Pittsburgh, PA)	0.1
TC	combustion	CNS analyzer (Elementar Analysensysteme GmbH, Hanau, Germany)	0.30
TN	combustion	CNS analyzer (Elementar Analysensysteme GmbH)	0.06
P (TP, PO_4–P)	EPA 365.1	DU 640 Spectrophotometer, Beckman (Krefeld, Germany)	0.01
NH_4–N	EPA 350.1	Auto Analyzer 3, Bran Luebbe (Norderstedt, DE)	0.009
NO_3–N	EPA 353.1	Ion Chromatography, Dionex (Sunnyvale, CA)	0.01
Ca (total and dissolved)	EPA 200.8	ICPMS, HP4500 PLUS, Hewlett-Packard Co. (DE)	0.01
Mg (total and dissolved)	EPA 200.8	ICPMS, HP4500 PLUS, Hewlett-Packard Co.	0.01
K (total and dissolved)	EPA 200.8	ICPMS, HP4500 PLUS, Hewlett-Packard Co.	0.01
Fe (total and dissolved)	EPA 236.2	AAnalyst 600, PerkinElmer (Shelton, CT)	0.01
Al (total and dissolved)	EPA 202.2	AAnalyst 600, PerkinElmer	0.01

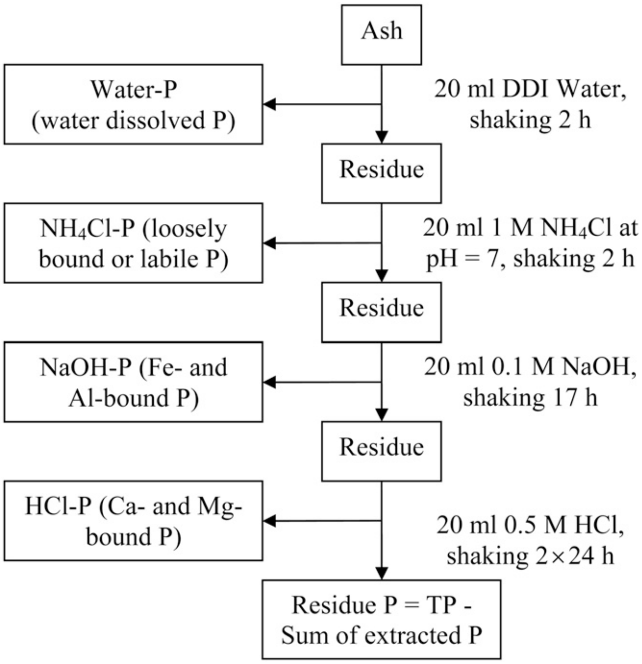

Fig. 2. The modified Hieltjes and Lijklema (1980) scheme used for plant ash P fractionation. DDI water, double deionized water;TP, total phosphorus.

total TK compared with corresponding dead leaves. Dead-leaf nutrients showed less between species differences compared with live-leaf nutrients. This difference of nutrient distribution in live and dead leaves can account for nutrient redistribution in ash by fire (Debano and Conrad, 1978).

All metals showed significant variation in total amount between the two species (Table 2). Total Mg (TMg), K (TK), Ca (TCa), and Fe (TFe) were statistically different among three sampling locations, and TK in live leaves were significantly greater than in dead leaves. Although TFe and TCa were also observed as significantly different between live and dead leaves, no trend was detected (Tables 2 and 3). Calcium is one of the dominant metals in species and live/dead leaf types, with concentrations around 1.0 to 1.5% in cattail and 0.2 to 0.6% in sawgrass. Potassium is also abundant in live leaves (approximately 0.7–1.7% in cattail and 0.5–0.8% in sawgrass). However, in dead leaves, total K was only 0.1 to 0.5% in cattail and around 0.2% in sawgrass. Total Mg was less than Ca and K but greater than Al and Fe, which were limited in amount (Table 3).

Potassium was the most abundant water-extractable cation in both species. On average, 63% of cattail and 66% of sawgrass TK was water soluble. Approximately 45 and 14% of total Mg and Ca, respectively, in cattail was water soluble, whereas approximately 20 and 16% of these two metals, respectively, was water soluble in sawgrass. No more than 0.1% of total Fe and Al were soluble for both species (data not shown).

Temperature Effects on Biomass and Total Nutrients in Residual Ash

Significant differences were observed for heating effects along a temperature gradient on TON, biomass, TN, and TC for all subsamples (Table 2 and Fig. 3). Total organic N was not detected after burning at 450 and 550°C, indicating nearly complete combustion of organic matter. Almost all samples lost around 99% of TN and TC via volatilization at 450 and 550°C. At these two temperatures, all leaf material was converted to white ash, whereas sawgrass produced less ash, with an average of 4% compared with 6% of ash generated by cattail. Black ash (charcoal) was found after burning at 350°C, and the organic matter combustion was about half at this temperature, ranging from 15 to 47% (average, 29%) for ash production. Volatilization of TN ranged from 27 to 70% (average, 47%), whereas TC volatilization ranged from 57 to 90% (average, 79%). Heating to 250°C yielded a reddish-black ash, which exhibited a distinct mass and TC loss compared with yellow residues observed with samples burned at 150°C, except sawgrass live leaf from the reference zone. Significantly greater TN loss was observed for the 250°C ash than 150°C residue in some cases; however, no significant differences of TN loss were identified for RCL, HCD, RCD, RSL, MSD, and RSD (Fig. 3).

No decrease was observed for TP and total metals with increasing burn temperature in terms of their dry leaf content due to their relatively high vaporization points and limited air movement in the muffle furnace. Figure 3 shows the ash TP (mg g^{-1} of ash) as related to leaf type and temperature for cattail and sawgrass from three nutrient-enriched zones, indicating the accumulation of TP in plant residue/ash with increasing temperature. Due to its high vaporization point (over 1000°C), TCa would not be lost through gaseous form under the burning temperatures applied in this study. Hence, TP/TCa ratios were used as an indicator for

Table 2. Summary of ANOVA results for main effects and interactions of temperature, species, nutrient impacted zone, and leaf type on nutrient composition. Temperature (T) includes 60, 150, 250, 350, 450, and 550°C; species (S) are cattail and sawgrass; nutrient impacted zone (H) indicates highly impacted, (M) moderately impacted, and (R) reference zones; and leaf type (L) refers to live and dead leaves.

Parameter	Temperature	Species	Habitat	Leaf type	T×S×L	T×I×L	T×I×S	T×S×I×L
pH	***	***	***	***	***	***	***	***
%Ash	***	*	***	**	NS	***	***	***
TN	***	***	***	***	***	***	***	***
TC	***	***	***	***	***	***	NS	***
TP	NS	***	***	***	NS	NS	NS	NS
TON	***	***	***	***	***	***	***	***
TMg	NS	***	***	***	NS	NS	NS	NS
TK	NS	***	***	***	NS	NS	NS	NS
TCa	NS	***	***	***	NS	NS	NS	NS
TFe	*	**	NS	**	NS	NS	NS	NS
TAl	NS	*	NS	NS	NS	NS	NS	NS
$\mathrm{PO_4}$–P	***	***	***	***	***	***	***	**
$\mathrm{NH_4}$–N	***	***	NS	***	***	***	NS	NS
$\mathrm{NO_2}$–N	***	***	***	***	***	***	***	***
$\mathrm{NO_3}$–N	***	***	**	NS	**	***	**	NS
$\mathrm{Mg^{2+}}$	***	***	*	***	***	***	***	***
$\mathrm{Fe^{2+}}$	NS	NS	NS	NS	NS	NS	NS	NS
$\mathrm{Al^{3+}}$	***	***	NS	NS	***	NS	NS	NS
$\mathrm{K^{+}}$	***	***	***	***	***	***	***	***
$\mathrm{Ca^{2+}}$	***	***	***	*	***	***	*	***

$*p < 0.05$; $**p < 0.01$; $***p < 0.001$; NS, not significant.

loss of P during combustion, similar to Smith et al. (2001) (Fig. 4). Although there were slight variations of TP/TCa ratios along burning temperatures, no significant difference was observed for sawgrass or cattail during laboratory simulation, implying no volatilization loss of P during combustion in muffle furnace.

Temperature Effects on Water-Dissolved Nitrogen and Phosphorus in Residual Ash

Significant effects of temperature were observed on water-dissolved N and P in ash (Table 2). Along the temperature gradient from 150 to 550°C, ammonia ($\mathrm{NH_4}$–N) concentrations had a significantly decreasing trend, with the lowest points at 450 and 550°C (Fig. 5). Unburned leaves (oven-dried at 60°C) contained greater $\mathrm{NH_4}$–N compared with burned leaves. Heating to 150°C reduced at least 88% of $\mathrm{NH_4}$–N in cattail live leaves and 65% of $\mathrm{NH_4}$–N in cattail dead leaves. Over 90% of $\mathrm{NH_4}$–N was lost after heating to 150°C for sawgrass live leaves, whereas around 50% of $\mathrm{NH_4}$–N remained in dead sawgrass leaves after heating to 150°C (Fig. 5). No pattern along the temperature gradient was detected for nitrite ($\mathrm{NO_2}$–N) and nitrate ($\mathrm{NO_3}$–N) (data not shown). Along the temperature gradient from 150 to 550°C, a spike was observed in water-dissolved inorganic P after heating live cattail leaves collected from the H and R zones to 350°C. A spike was also observed for sawgrass

Table 3. Variation of total nutrient content in oven-dried leaves among 10 subsamples. All values presented are mean concentrations ($n = 3$). Differences among 10 subsamples were examined by Duncan's mean separation: *a > b > c > d > e > f > g*. Numbers with the same letter within the same measurement are not significantly different ($p < 0.05$). Total nitrogen (TN), total carbon (TC), total organic nitrogen (TON), total phosphorus (TP), total magnesium (TMg), total potassium (TK), and total calcium (TCa) are expressed as mg g^{-1} of dry leaf material; total iron (TFe) and total aluminum (TAl) are expressed as µg g^{-1} of dry leaf material. The greatest value for each parameter is bolded and italicized.

Leaf type	TP	TN	TC	TON	TK	TMg	TCa	TFe	TAl
Cattail									
Live leaf									
H zone	***1.18*** a	***10.52*** a	413.86 g	***9.50*** a	14.08 b	***2.35*** a	***13.67*** ab	22.92 c	***62.81*** a
M zone	0.56 c	9.37 b	441.43 e	7.52 b	7.67 c	1.67 b	***14.92*** a	23.76 c	***57.37*** ab
R zone	0.54 c	9.06 b	442.84 e	8.02 b	***17.40*** a	***2.57*** a	***11.62*** ab	23.60 c	***59.21*** ab
Dead leaf									
H zone	0.21 d	4.56 e	435.49 f	4.47 d	1.89 e	1.05 bc	***11.77*** ab	24.82 c	***58.95*** ab
M zone	0.16 d	3.69 f	***458.40*** ab	3.39 e	1.38 e	1.25 b	***11.91*** ab	22.77 c	***44.30*** ab
R zone	0.15 d	3.10 f	453.03 cd	3.05 e	4.59 d	1.59 b	10.58 b	18.57 c	***66.99*** a
Sawgrass									
Live leaf									
M zone	0.63 b	8.18 c	***460.94*** a	7.80 b	7.55 c	0.45 c	1.65 e	19.30 c	***47.00*** ab
R zone	0.21 d	5.41 d	456.60 bc	5.27 c	4.84 d	0.50 c	1.90 de	35.55 b	34.80 b
Dead leaf									
M zone	0.17 d	3.83 ef	450.57 d	3.79 de	2.43 de	1.29 b	4.97 cd	29.27 bc	***56.93*** ab
R zone	0.05 e	3.81 ef	449.40 d	3.76 de	2.00 e	1.36 b	6.34 c	***56.61*** a	***51.39*** ab

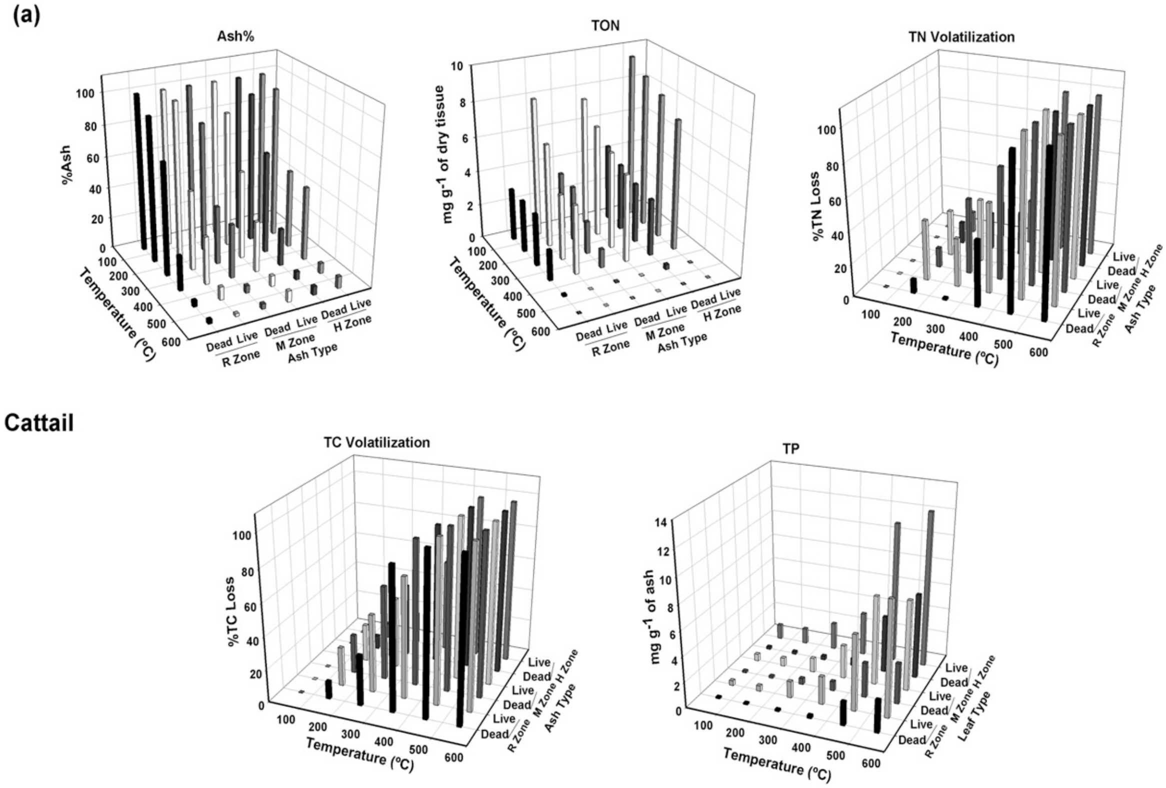

Fig. 3a. Differences in total organic nitrogen (TON), ash production (%ash), total nitrogen (TN) volatilization (%), total carbon (TC) volatilization (%), and total phosphorus (TP) content in ash along a temperature gradient for live and dead leaves of cattail collected from three nutrient impacted zones (i.e., highly impacted zone [H zone], moderately impacted zone [M zone], and reference zone [R zone]).

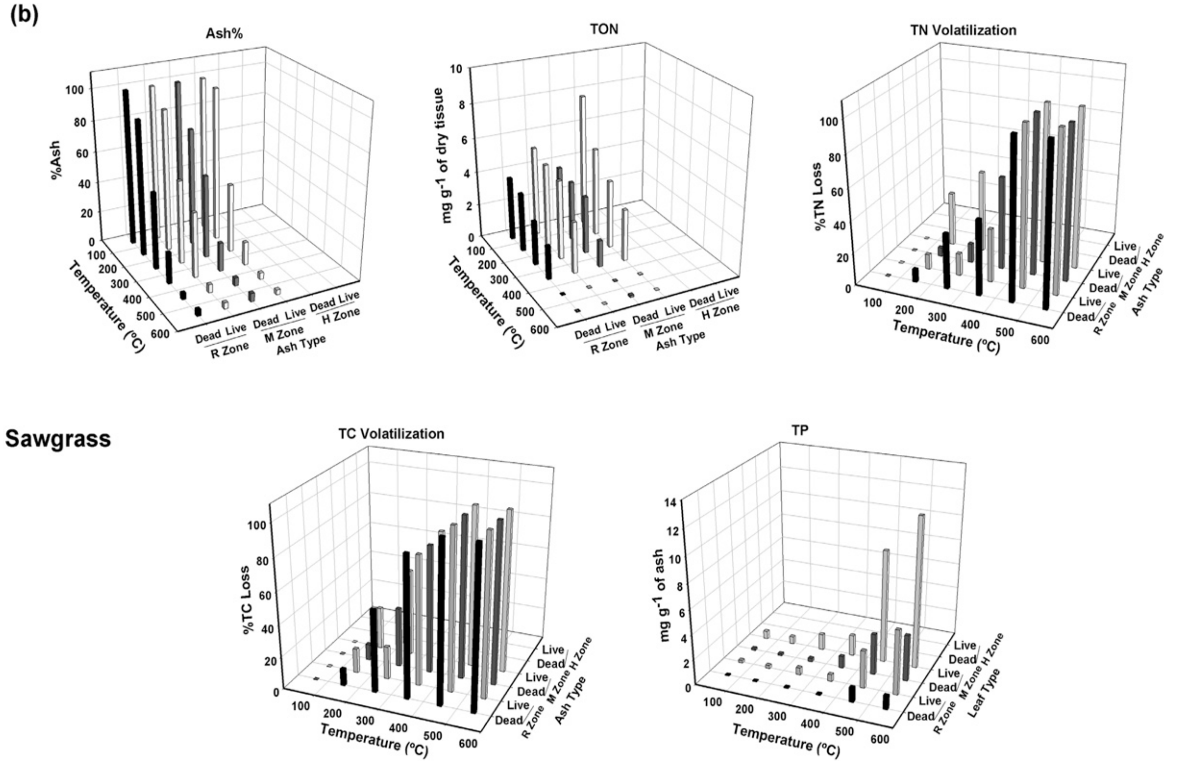

Fig. 3b. Differences in total organic nitrogen (TON), ash production (%ash), total nitrogen (TN) volatilization (%), total carbon (TC) volatilization (%), and total phosphorus (TP) content in ash along a temperature gradient for live and dead leaves of sawgrass collected from three nutrient impacted zones (i.e., highly impacted zone [H zone], moderately impacted zone [M zone], and reference zone [R zone]).

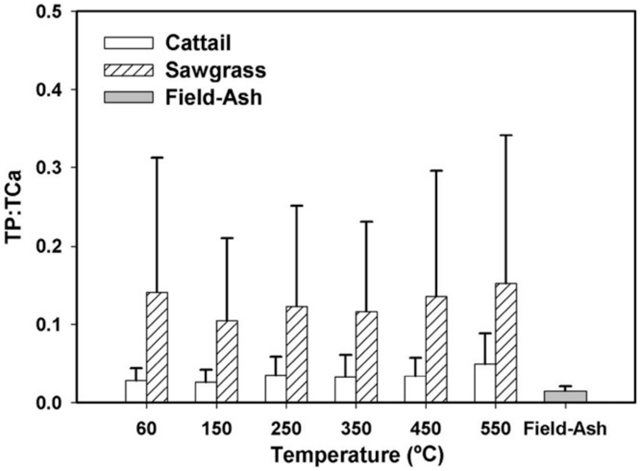

Fig. 4. The ratios of total phosphorus (TP) and total calcium (TCa) for residue/ash of cattail (from highly impacted, moderately impacted, and reference zones) and sawgrass (from moderately impacted and reference zones) burned along a temperature gradient in the laboratory and for ash collected after a prescribed fire in the field from highly impacted zone (H2 area). Bars are expressed as means plus SD.

live leaves from the R zone but not for dead leaves. For all subsamples, burning at 450 and 550°C produced significantly less PO_4–P in ash. Dead sawgrass leaf burned at 150°C from the M zone had significantly greater PO_4–P than that burned under other temperatures (Fig. 5). Compared with PO_4–P in oven-dried samples, PO_4–P in different leaf types (dead vs. live) showed different responses to heating or burning. Water-dissolved P in live leaves of both species decreased after heating to each temperature (from 150 to 550°C), whereas increased PO_4–P in all dead leaves except sawgrass from the M zone was observed after heating to 350 or 250 or 150°C (Fig. 5).

Water-Soluble Metals and pH in Plant and Residual Ash along the Temperature Gradient

Despite some variations in pH among the 10 subsamples, there were similar increasing trends in pH along the temperature gradient from acid to alkaline for all subsamples. Figure 6 presents boxplots for the pH values of leaf or ash materials after heating to various temperatures. The median pH value is 4.5 for oven-dried plant leaves (60°C), with a slight increase to 4.9 at 250°C, then a jump to 7.3 at 350°C, and reaching 10.0 at 450°C with little change at 550°C (Fig. 6). This significant increase in pH of burned plant residues was attributed to base cation release during combustion, which could alter soil pH and affect soil nutrient availability (Ulery et al., 1993; Dikici and Yilmaz, 2006; Murphy et al., 2006b).

Temperature significantly affected water-soluble metals except Fe^{2+}, but the responses were very different (Table 2). For example, live cattail leaf from the H zone (HCL) had Al^{3+} concentrations significantly greater after heating to 150°C than after heating to 250, 450, and 550°C, whereas no significant difference was observed between 150 and 350°C or 350 and 550°C. In contrast, K^+ was significantly greater in 350 and 550°C HCL than in 150 and 250°C HCL. No significant difference between 450 and 550°C or between 450 and 150°C was detected for K^+ in HCL. Furthermore, concentrations of K^+ in 350 and 550°C HCL were similar to that in 60°C oven-dried leaves (data not shown).

Phosphorus Fractionation in Completely Burned Ash

After burning at 450 and 550°C, water-extractable P showed the least variation within species, sampling plots, burning temperatures, and leaf type (live vs. dead). Only the between-species difference was significant. Temperature and interactions of plot×species×type×temperature had no significant effects on the HCl-extractable P fraction variance. Residual P was not significantly different between live or dead leaves (ANOVA table not shown). Figure 7 shows the results of P fractionation for live and dead leaves of cattail and sawgrass from the moderately impacted zone, which were burned at 450°C. A similar distribution of P fractions was found within the same species, sampling location, and leaf type. Subsamples burned at 550°C exhibited a similar distribution of P fractions as those burned at 450°C. Overall, HCl-extractable P (average of 50%) and NH_4Cl-extractable P (average, 33%) are by far the predominant P components, followed by residual P (average, 16%). Water-extractable P and NaOH-extractable P were minor fractions (average, 0.2 and 0.8%, respectively) and were not detectable in some cases.

Significantly greater amounts of labile inorganic P (mainly NH_4Cl-extractable P with an average of 56%) remain in the sawgrass ash versus the cattail ash (Fig. 7). However, fixed inorganic and residual P are major components in cattail ash, with an average of 67% of HCl-extractable Ca/Mg-bound P and 14% of residual P. Almost no Fe and Al fixed P (NaOH-extractable P) was detected for cattail ash (average, <0.01%); however, an average of 2% of Fe/Al-associated P was found in sawgrass ash.

Comparisons in Total Nutrient and Burning Temperature between Laboratory-burned Ash and Field-collected Ash

The TP/TCa ratio of field-collected ash was close to but lower than that of cattail ash burned in the laboratory, indicating that the vegetative community in the field mainly consisted of cattail (Fig. 4). The cause of a lower TP/TCa ratio for cattail field ash than for laboratory-burned cattail ash might be the nonparticulate loss of P or more accumulation of Ca during the prescribed fire.

Figure 8 shows the estimation of average burning temperature during the field-prescribed fire based on the results of the laboratory study using Eq. [1]. The circle-line curves were made from laboratory simulation results, and the single triangles with whiskers were the field-collected ash data. As observed during field fire, the cattail live leaf was not converted to ash; rather, it was standing dead and fell down in a couple of days. That is, the field-collected ash consisted mainly of cattail dead leaf. Hence, using the laboratory-burning curves of cattail dead leaf, the estimated average temperature of field fire was approximately 400°C.

Figure 9 presents the comparisons of P fractions between field-collected ash and laboratory-burned ash. The ash collected from the field was most comparable to laboratory-burned ash of dead cattail leaves from the H zone. Calcium/Mg-fixed inorganic P is

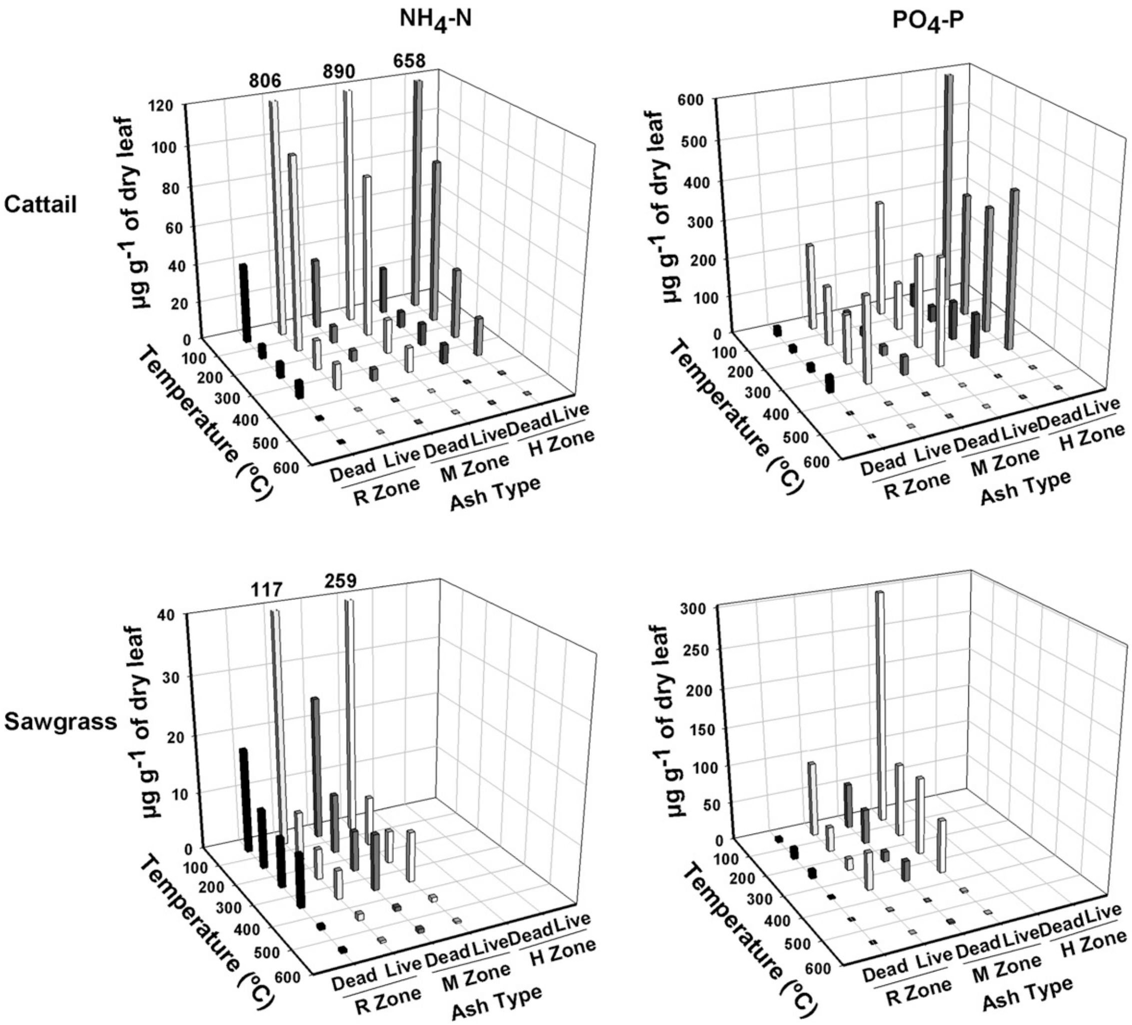

Fig. 5. Temperature effects on mean water-dissolved nitrogen (N) and phosphorus (P) concentrations in plant residue/ash. Ash type indicates ash samples generated from burned live and dead leaves of cattail and sawgrass from three nutrient impacted zones (i.e., highly impacted [H], moderately impacted [M], and reference [R] zones, which are the same as in Fig. 3). Due to the relatively high values, concentrations of ammonia (NH_4–N) in oven-dried live leaves of cattail and sawgrass are indicated above their corresponding columns as follows: 806, 890, and 658 μg g^{-1} of dry leaf for live leaves of cattail from R, M, and H zones; 117 and 259 μg g^{-1} of dry leaf for live leaves of sawgrass from R and M zones, respectively.

a major fraction of the field ash (average, 64%), followed by residual P (average, 32%), then labile NH_4Cl-extractable inorganic P (average, 3%). The remaining percentage (≤1%) was shared by Fe/Al-associated P and water-soluble P. Compared with cattail ash burned in the laboratory at 450°C, which contains an average of 19% of NH_4Cl-extractable P, the most notable difference is the much lower extractable inorganic P concentration in the field ash (3% of NH_4Cl-extractable P). Furthermore, the field ash contained on average 18% more residual P than did cattail laboratory ash.

Discussion

Nutrient Concentration in Cattail and Sawgrass along the Nutrient Gradient

Nitrogen and P in plant leaves are good indices for nutrient gradients along sampling locations, implying the effects of a soil nutrient gradient from a highly impacted zone in the north to the reference areas in south on plant growth. Our results agree well with a previous study (Miao and Sklar, 1998) in which a decrease of leaf TP from 605 to 248 mg kg^{-1} for sawgrass and 1175 to 556 mg kg^{-1} for cattail were observed from P-enriched to reference plots in WCA 2A. Similar findings were reported previously (Richardson et al., 1999; Noe et al., 2001). Furthermore, the plant mass N/P ratios suggest increased P limitation from the highly enriched to the non-enriched zones. That is, considering the nutrient-limitation criteria by Koerselman and Meuleman (1996), plants with mass N/P ratios over 16 (>36 molar ratio) are P limited, below 14 (<31 molar ratio) are N limited, and between 14 and 16 could be N or P limited. In this study, the mass N/P ratios were 8.9, 16.7, and 16.8 for cattail live leaves from the H, M, and R zones and 13.0 and 25.8 for sawgrass live leaves from the M and R zones. Richardson et al. (1999) reported a similar P-limitation gradient in Everglades.

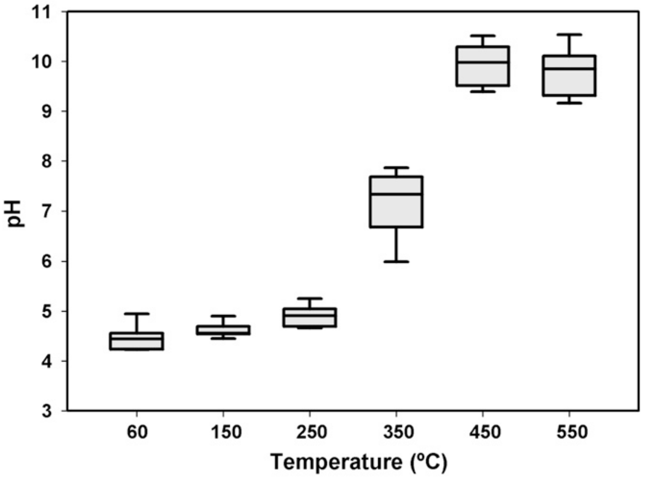

Fig. 6. Increasing trend of pH values for plant/ash with increasing burning temperature. Each box includes data for all samples (live and dead leaves of cattail and sawgrass from three nutrient impacted zones; i.e., highly impacted [H], moderately impacted [M], and reference [R] zones) burned at corresponding temperature. The solid lines within the box represent medians; the lower and upper whiskers are 10th and 90th percentiles, respectively; and the lower and upper boundaries of the boxes are 25th and 75th percentiles, respectively.

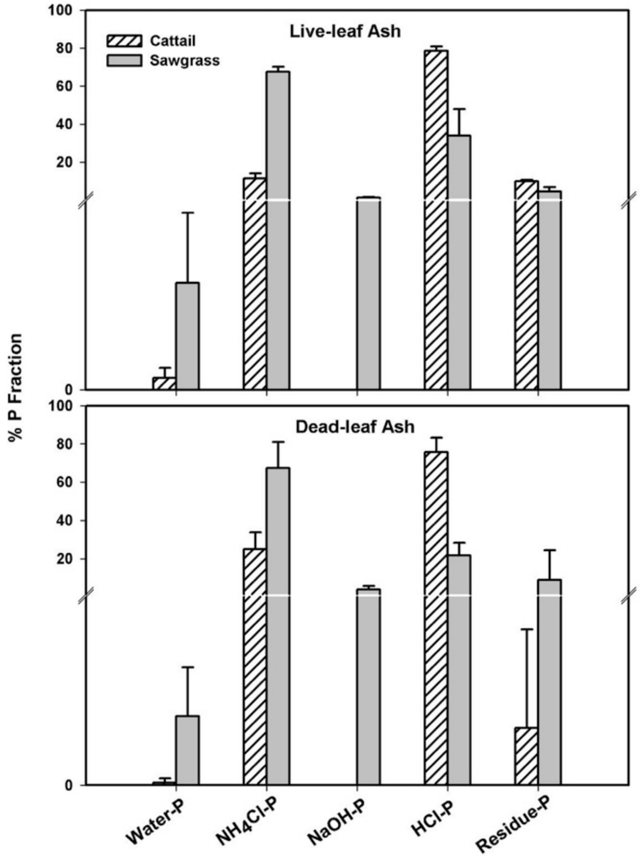

Fig. 7. Phosphorus (P) fractions for ash resulting from the burning of live and dead leaves of cattail and sawgrass from moderately impacted zone at 450°C. Bars are expressed as means and SD.

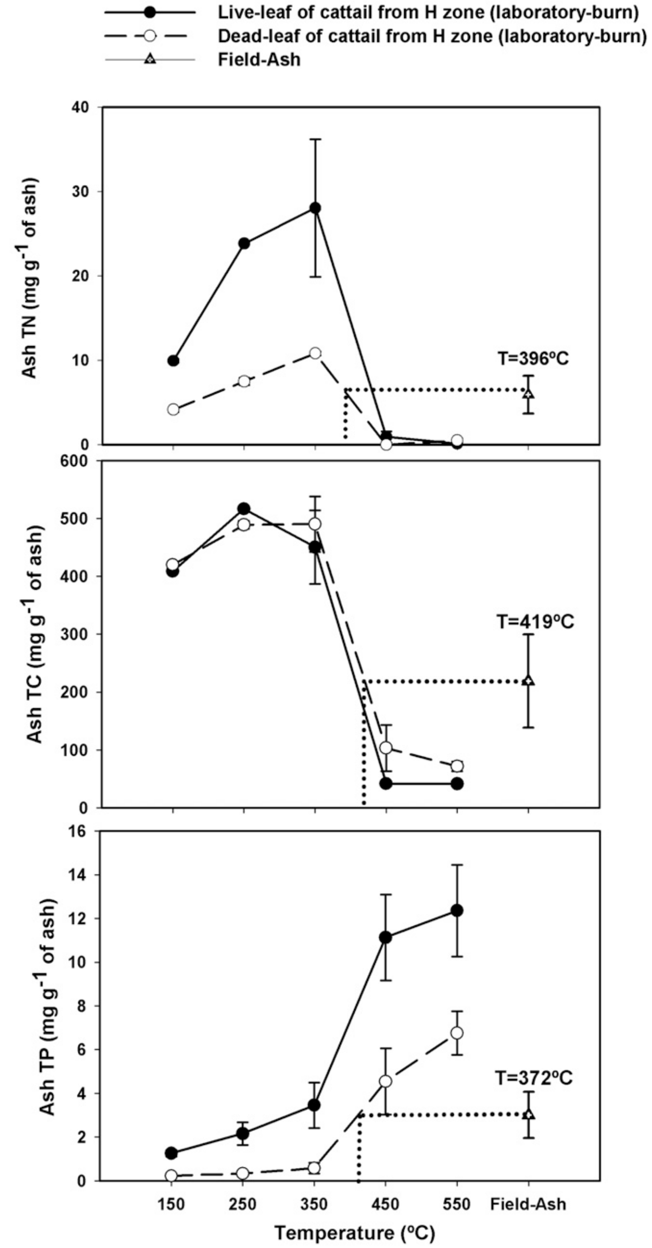

Fig. 8. Estimating the average temperature of prescribed fire using the results of laboratory simulation. TN, total nitrogen; TC, total carbon; and TP, total phosphorus. Data are expressed as means (circles or triangles) plus SD (whiskers).

Effects of Burn Temperature on Plant Ash Nutrients

Significant temperature effects on plant ash nutrient composition and availability were observed. As expected, fires burning at high temperatures (over 450°C) resulted in substantial removal of C and N (over 99%) from the plant ash. Compared with TN and TC, TP recoveries showed no evident patterns along the temperature gradient in the laboratory simulation. This implies that the combustion conditions applied in this study resulted in little volatilization of P due to minimal air movement under laboratory conditions and the relatively high volatilization temperature of P. Similarly, Gray and Dighton (2006) reported dramatic decreases in N (>99%) but no significant variations in

TP on heating to 550°C regardless of species. Nearly complete organic matter combustion at temperatures of 400 to 500°C was previously documented (Marion et al., 1991; Certini, 2005).

Nutrient redistribution in the residue/ash by burning temperature varied between species, nutrient gradient of soil, and leaf type (live or dead leaves), similar to previous reports (Debano and Conrad, 1978; Gray and Dighton, 2006). Total P, Mg, K, and Ca showed greater levels in cattail ash than in sawgrass ash, whereas Fe was slightly higher in sawgrass ash. Cattail ash from H and R zones showed similar TP content, which was approximately two times that in ash from the M zone, although baseline TP level was found to be the greatest in oven-dried leaf from the H zone. For sawgrass, more TP was found in ash burned with leaf from the M zone than that from the R zone. Ash burned from live leaves contained more P and K, whereas dead-leaf ash contained more Ca, Fe, and Al, regardless of species and habitat. These differences may be a result of differences in structural and metabolic compounds in the different subsamples (Gray and Dighton, 2006).

Compared with the ash burned in the laboratory, the field-collected ash retained more N and C but less P. No more than 0.03% of TN and 0.5% of TC were observed in laboratory-burned ash, whereas 0.6% of TN and 21.9% of TC were observed in field-collected ash. The TP remaining in ash collected from the field was around 60% of that remaining in laboratory-burned ash. Previous studies suggested that during a field fire, the nonparticulate loss of N might be less, whereas the vaporization of P could be more than laboratory estimates suggest (Raison et al., 1985; McNaughton et al., 1998). This difference could be the result of the particulate or nonparticulate loss of P or the variations in vegetative community found in the field. Thus, after burning at 450 to 550°C, most of the C and N are removed from the burn site and not available for plant growth, whereas a large amount of P is retained in the ash and redistributed in the environment.

A shift of the water-soluble inorganic N from NH_4–N to NO_2–N and NO_3–N was observed along a temperature gradient, indicating oxidation of NH_4–N during heating and the loss through volatilization of inorganic N. A dramatic decrease of water-soluble P was found after burning at higher temperatures (over 450°C) for all samples. However, dead-leaf samples showed increased water-soluble P after burning at 350°C (or lower temperatures), except for sawgrass from the M zone, compared with unburned (oven-dried) samples. This implies that a low-intensity fire could increase P availability, whereas an intense fire generally resulted in a decrease of water-soluble P. A low ratio of water-dissolved P to TP was also observed for field-collected ash. Decreasing water-dissolved P due to combustion was previously reported by Gray and Dighton (2006).

Although metal concentrations may be similar in burned or unburned leaves, they may exist in different forms in ash, compared with those in unburned leaves. Basic cations are converted from organic compounds to oxides during combustion, which subsequently form hydroxides and carbonates once exposed to the ambient environment and eventually accumulate in the environment (Ulery et al., 1993). During an intensive field fire, a significant nonparticulate loss of K could occur (Raison et al., 1985). In our study, no volatilization was observed for total metals by heating leaf material over a range of temperatures in the muffle furnace. However, the field-collected ash contained 76% less total K compared with laboratory-burned ash burned at 450°C with dead leaf of cattail from the H zone.

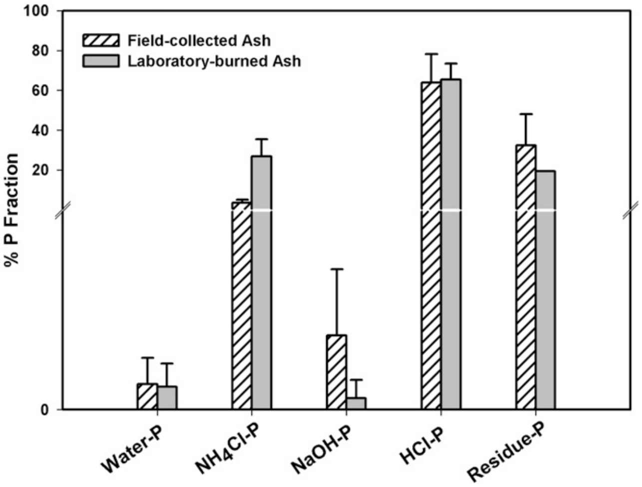

Fig. 9. Phosphorus (P) fractions for cattail dead-leaf ash from a highly impacted zone (H zone). Ash was collected from the field after a prescribed fire in July 2006 or burned in the laboratory at 450°C. Bars are expressed as means and SD.

Phosphorus Fractions in Plant Ash

In previous studies, a dramatic increase in the TP/soluble P ratio was found in ash of forest tree species after an intensive fire and contributed to the binding of inorganic P to basic oxides (Raison et al., 1985; Gray and Dighton, 2006). However, data on P fractions in plant ash are limited. A detailed fractionation of plant ash will provide useful information with respect to the assessment of P in the environment.

Ammonium chloride–extractable P is one of the major fractions for all samples. Significantly greater NH_4Cl-extractable P was found compared with other fractions (water-, HCl$^-$, and NaOH-extractable and residual P) in all sawgrass subsamples except the live leaf of sawgrass from the R zone burned at 550°C. Furthermore, sawgrass retained more NH_4Cl-extractable P than cattail. Neutral salt–extractable inorganic P is considered bioavailable because of its labiality when entering the water column and soil porewater (Reddy et al., 2005). Hence, sawgrass ash has a greater potential to release available P than cattail.

Another dominant form is HCl-extractable P regardless of species, nutrient impacted zone, and leaf type. Residual P is also abundant for both species. Approximately 81% of TP in cattail was converted to Ca/Mg bound P (67%) or residual P (14%) in the laboratory experiments, and over 95% of TP in field collected ash was Ca/Mg fixed or residual P. Approximately 44% of TP was fixed for sawgrass. Inorganic P associated with Ca/Mg is relatively stable under alkaline pH levels and is not readily available or may form unavailable compounds, such as apatite. Residual P includes unavailable inorganic P that is not extractable with alkali or acid and highly resistant organic P (Hieltjes and Lijklema, 1980; Reddy et al., 2005). Thus, an intense fire could be an effective method to reduce the P availability within an ecosystem.

Aluminum- and Fe-associated P were minor components in all ash samples analyzed regardless of species, nutrient impacted zone, and leaf type. This could be the result of the limited amount of total Fe and Al in cattail and sawgrass (up to 0.1% in ash; data not shown) as well as the alkaline character of the ash, which causes desorption of P from Fe and Al hydrous oxide surfaces (Murphy et al., 2006b). This redox-sensitive P is not readily available but may become available under anaerobic conditions (Murphy et al., 2006a).

The following differences were observed for P fractions between laboratory-burned and field-collected ash: The TP in the laboratory ash is 1.7 times more than that in the field ash; the average level of NH_4Cl-extractable P in laboratory ash is 1869 mg kg^{-1}, which is 6.8 times more than that in the field ash; and even for relatively persistent Ca/Mg-bound P, nearly double the amount was found in laboratory ash, although both ashes have similar proportions of Ca/Mg-fixed P. There might be several factors contributing to such differences. First, based on the nutrients remaining in the field-collected ash, it can be estimated that the black-white field ash was burned at an average temperature of 400°C (Fig. 8). However, the laboratory ash was produced under a more uniform temperature of 450°C. Thus, the incomplete combustion of organic matter, including organic P, which may eventually be converted to residual P, could be expected in the field ash. Second, the ash that was collected from the field (H2 area) mainly consisted of dead-leaf ash of cattail and contained only a few live and dead-leaf ashes of sawgrass, whereas the corresponding laboratory-burned ash was solely derived from dead leaf of cattail. Third, differences in ash age and the ambient environment (e.g., rainfall and wind) between the field and laboratory ashes might induce the differences in ash nutrient compositions (Ulery et al., 1993). Contrary to the laboratory ashes that were analyzed fresh, the field ash was stored for several months before analysis. During a field fire, P in plant and litter could be lost through a nonparticulate pathway (e.g., form P_2O_5 gas; Raison et al., 1985), whereas in a laboratory muffle furnace with limited air movement, P stays within the beakers during heating (Gray and Dighton, 2006).

Large amounts of P were precipitated with Ca and Mg under high pH conditions. Such precipitation could occur during the burning (with basic oxides in the ash) or after exposure to ambient environmental conditions (with basic hydroxides and carbonates) (Ulery et al., 1993; Gray and Dighton, 2006). Although the decrease of water-soluble P and the increase of fixed P in firmly held forms were previously reported for plant residual material (Gray and Dighton, 2006), the P fractionation using sequential extraction to assess the P availability remained unknown, to the best of our knowledge. Within this relatively simplified scheme modified from Hieltjes and Lijklema (1980), we quantified water-soluble, labile, Al- and Fe-associated, Ca- and Mg-bound, and residual (if any) portions of P of plant ashes collected from the laboratory simulations and the field, thus providing an understanding of fire effects on ash P fractions and their eventual impacts on the environment.

Implications to Wetland Management

Prescribed fires have been extensively applied as a management tool in a wide range of habitats and ecosystems since the 1970s (Wan et al., 2001) for a variety of purposes, including nutrient release (Concilio et al., 2005), fuel-reduction management on wildlife (Bury, 2004; Stephens et al., 2004; Úbeda et al., 2005), managing exotic species and facilitating native species re-establishment (Quinlan et al., 2003; Lee et al., 2005; Miao and Carstenn, 2006; Murphy et al., 2006a), and other purposes (Brockway et al., 2002). Burning intensity differs depending on the purpose and the burned system. For example, in wetlands, depending on fuel load, water depth, and weather conditions, fire can consume the aboveground biomass (surface fire) only or destroy all existing vegetation, a portion of the seed bank, and damage the soil layer (peat fire) (Smith et al., 2001). This study provided insight on the impacts of fire temperature on the availability of nutrients as suspected by fire managers. The relationship between burn temperature and form of P seemed to be predictable and provided information for wetland elemental modeling associated with fire. Intense fires (over 450°C) eliminate N in plants and litter and reduce ash P availability, which reduces N and P loads in the burned area and hence may favor organisms capable of atmospheric N_2 fixation (McCormick et al., 1999; Inglett et al., 2004; Scott et al., 2005). On the other hand, less intense fires could induce elevated P availability in plant residue. During a field fire, the nonparticulate loss of P can occur (28–88%), whereas the forms of volatilized P (P_4O_{10} or P_4O_6) depend on combustion conditions (Raison et al., 1985). However, fire-induced nutrient release is probably within the range of natural variations, and fire impact on nutrient availability is temporal (Miao and Carstenn, 2006; Murphy et al., 2006b).

The study showed that intense fires tend to accelerate the precipitation of P with Ca/Mg in ash in ecosystems suffering from P enrichment, including the Everglades and Stormwater Treatment Areas that are designed to reduce phosphorus loading into the Everglades Water Conservation Areas. However, further studies are necessary to evaluate the environmental impacts of fire and ash with a consideration of environmental fate of ash nutrient, including aerial deposition of smoke and ash, release of ash nutrients into the water column and sediments, and the redistribution of ash nutrients into the adjacent ecosystems.

Biological traits of vegetation (i.e., dominant plant species and their nutrient allocation and redistribution in live and dead leaves) are important factors when determining burn strategy and estimating post-fire ash nutrient release. For example, cattail and sawgrass showed different responses to burning. Although live and dead leaves of sawgrass can be consumed during a field fire, only dead leaves of cattails burn. Cattail live leaves do not usually burn; rather, they stand dead and fall down in a couple of days, becoming a nutrient source. Although these heated dead plants could experience similar processes of nutrient release as normal dead leaves (i.e., mineralization [decomposition and decay]), the amount of nutrient released may differ due to significant differences between live and dead leaves in leaf nutrient concentrations as identified in this study. Furthermore, sawgrass ash contains a greater proportion of labile P compared with cattail ash, whereas cattail ash contains more TP than sawgrass ash.

Overall, ecosystem management using prescribed fires should take into consideration fire intensity, which is related to the quantity (litter amount) of fuel energy and environmental conditions such as season and weather, to achieve the desired results of the fire (e.g., removing undesired nutrients or species, facilitating germination and growth of desired species, and minimizing the extent and severity of wildfires, etc.).

Conclusions

Significant decreases in leaf TC and TN content were observed with increasing fire temperature, and organic matter combustion was nearly complete at temperatures of 450°C or greater. Recovery of total P and metals exhibited small differences regardless of burn temperature; however, these components could be converted from organic compounds to inorganic forms during combustion. Due to the high pH value of ash, basic cations (with Ca and K as major forms) were transformed to oxides, which subsequently converted to hydroxides and carbonates once exposed to the ambient environment. The P fractionation results with regard to completely burned ash in the laboratory experiments suggested that HCl-extractable P (average, 50%) and NH_4Cl-extractable P (average, 33%) are by far the dominant P components, followed by residual P (average, 16%). Water-extractable P and NaOH-extractable P are minor fractions (average, 0.2 and 0.8%) and are not detectable in some cases. Compared with laboratory-burned cattail ash, field-collected ash contained 18% more residual P and 16% less NH_4Cl-extractable P on average. This indicates that field ash has less P lability resulting from different temperatures and exposure to the surrounding environment (air movement, rainfall). In conclusion, this study provides meaningful information with regard to the restoration and fire management of wetland ecosystems (e.g., if the purpose of a prescribed fire is to reduce nutrient accumulation and fuel load, intense fires [>450°C] may be considered); on the other hand, less intense fires could be used to retain P for the regrowth of certain species.

Acknowledgments

We thank the South Florida Water Management District and IFAS/TREC of the University of Florida for support of this research. We also thank Kati W. Migliaccio, Cassondra R. Thomas, Thomas Dreschel, and Pat L. Beyer for reviewing this manuscript. We gratefully acknowledge the assistance of Yong Cai for providing instruments for metal analyses; Guiqin Yu for dissolved nitrogen analyses; Guangliang Liu for the preparation of three-dimensional graphs; Chris Edelstein, Bob Johnson, Erik Sindhoj, Christina Stylianos, and Daniel Salembier for assistance in the design and construction of the field ash collectors and collection of the field ash; and Susan Hohner for providing the GIS map.

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