Estimation of Postfire Nutrient Loss in the Florida Everglades

Y. Qian University of Florida
S. L. Miao and B. Gu South Florida Water Management District
Y. C. Li* University of Florida

Postfire nutrient release into ecosystem via plant ash is critical to the understanding of fire impacts on the environment. Factors determining a postfire nutrient budget are prefire nutrient content in the combustible biomass, burn temperature, and the amount of combustible biomass. Our objective was to quantitatively describe the relationships between nutrient losses (or concentrations in ash) and burning temperature in laboratory controlled combustion and to further predict nutrient losses in field fire by applying predictive models established based on laboratory data. The percentage losses of total nitrogen (TN), total carbon (TC), and material mass showed a significant linear correlation with a slope close to 1, indicating that TN or TC loss occurred predominantly through volatilization during combustion. Data obtained in laboratory experiments suggest that the losses of TN, TC, as well as the ratio of ash total phosphorus (TP) concentration to leaf TP concentration have strong relationships with burning temperature and these relationships can be quantitatively described by nonlinear equations. The potential use of these nonlinear models relating nutrient loss (or concentration) to temperature in predicting nutrient concentrations in field ash appear to be promising. During a prescribed fire in the northern Everglades, 73.1% of TP was estimated to be retained in ash while 26.9% was lost to the atmosphere, agreeing well with the distribution of TP during previously reported wild fires. The use of predictive models would greatly reduce the cost associated with measuring field ash nutrient concentrations.

The Florida Everglades, which occupies an area of approximately 6200 km^2, is one of the largest and most unique wetlands in the world. Although this highly P limited freshwater wetland was historically sawgrass [*Cladium mariscus* (L.) ssp. *jamaicense* (Crantz) Kük] dominant, thousands of hectares have been replaced by cattail (*Typha domingensis* Pers.) which is characteristic of P-enriched habitats (Miao and Sklar, 1998; Richardson et al., 1999), due to anthropogenic activities. These activities are leading 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; Noe and Childers, 2007). To accelerate the ecosystem recovery process, active management of the existing cattail marsh, including prescribed fires, is considered a potential tool for Everglades restoration (Miao and Carstenn, 2006; Qian et al., 2009). A large-scale and long-term ecosystem study (the Fire Project) is currently conducted in Water Conservation Area 2A (WCA 2A) to assess whether repeated fire can be an effective management tool to accelerate recovery in highly nutrient enriched area (Miao and Carstenn, 2006). On the other hand, anthropogenic activities (e.g., changes in land use and climate) can increase the risk of a wildfire, which is an essential process in South Florida to regulate the structure and function of ecosystems (Wade et al., 1980). Therefore, it is essential to evaluate nutrient composition of plant ash and redistribution from plant ash into the sediment-water system, for assessing fire effects on nutrient availability in the Everglades.

Nutrient transport during and postfire have been studied previously. The pathways through which nutrients contained in vegetation or surface soil are redistributed by a fire are via nonparticulate (volatilization) and/or particulate (ash) pathways (Raison et al., 1985). Nutrients (e.g., C, N, and S) with relatively low volatilization temperature are most likely removed from the burned site through volatilization and result in atmospheric pollution (Cachier et al., 1995; McNaughton et al., 1998; Liu et al., 2000; Wan et al., 2001). Otherwise, nutrients remaining in ash can be redistributed to adjacent areas via wind, rainfall, erosion, runoff, and leaching, or be deposited onsite and thus may have a significant impact on the soil nutrient status

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*Corresponding author (yunli@ufl.edu).
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677 S. Segoe Rd., Madison, WI 53711 USA

Y. Qian and Y.C. Li, Tropical Research & Education Center, Soil and Water Science Dep., IFAS, Univ. of Florida, 18905 SW 280th St., Homestead, FL 33031; S.L. Miao and B. Gu, South Florida Water Management District, 3301 Gun Club Rd., West Palm Beach, FL 33406.

Abbreviations: DA, discriminant analysis; DDI water, double deionized water; H zone, highly-impacted zone; MLR, multiple linear regression; M zone, moderately-impacted zone; R zone, reference zone; WCA 2A, Water Conservation Area 2A.

and water quality (Hauer and Spencer, 1998; Thomas et al., 1999; Badía and Martí, 2003; Townsend and Douglas, 2004).

Factors determining the postfire nutrient budget are the prefire nutrient content in the combustible biomass, fire intensity (burn temperature and duration), and amount of combustible biomass. It is commonly accepted that C, N, and S are the nutrients that are lost in the greatest quantity; loss of P is intermediate and varies with species and locations; and metals, particularly Ca are not volatilized during fire, although the gaseous loss of K was previously reported (Raison et al., 1985; Kauffman et al., 1994; Murphy et al., 2006; Holdo et al., 2007). Researchers estimate a postfire nutrient budget mainly using the following methods: (i) controlled field fire with thermocouples to measure fire temperature, analyzing pre- and postfire biomass and nutrients (McNaughton et al., 1998); (ii) measuring fuel loads, fire-consumed biomass, and nutrients in pre- and postfire plant materials, further partitioning nutrient loss into the amount lost through volatilization and particulates using Ca as an indicator (i.e., assuming all loss of Ca will be through particulate losses) (Raison et al., 1985; Kauffman et al., 1994); and (iii) using a meta-analysis method to synthesize data from previous studies to develop comprehensive and quantitative models (Wan et al., 2001).

However, these methods did not give a complete picture of nutrient composition in plant ash along a temperature gradient. This may require the determination of the fire temperature during a fire, which may not be possible for an unpredicted wildfire. Here, we report a method to determine the average burn temperature of a prescribed fire and thus predict the nutrient concentrations in the postfire plant ash, on the basis of a laboratory simulation and field-collected ash nutrient analyses; and the further partitioning of P into the amount that is retained in plant ash and that lost as particulates. Predictive models will be interesting to ecosystem managers who are concerned about fire impacts on nutrient enrichment and restoration of an ecosystem, for example, P-enrichment and exotic species invasions in the Florida Everglades (Miao and Carstenn, 2006). Specifically, our objective was to quantitatively describe the relationships between nutrient loss (or concentrations in ash) and burning temperature in laboratory controlled combustion, to predict the temperature of field fire, and further to predict nutrient concentrations in field ash based on the temperature information predicted. The establishment of predictive models for nutrient concentrations in ash, if successful, would greatly reduce the cost associated with measuring field ash nutrient concentrations. Moreover, these predictive models are particularly useful for estimating the amount of element (e.g., P) retained in the ash and lost to the atmosphere, which cannot be directly measured. In addition to conducting laboratory experiments, we also conducted a prescribed fire in the northern Everglades. The data obtained in laboratory experiments were used to establish predictive models and the total P (TP) budget of this prescribed fire was estimated based on these models and available field data.

Materials and Methods

Site Description

Live and dead leaves of sawgrass and cattail were collected from WCA 2A within the northern Everglades: a highly-impacted zone (H zone, 26°34′ N and 80°37′ W; 1000 to 2000 mg P per kg soil), a moderately-impacted zone (M zone, 26°32′ N, 80°38′ W; 600–1000 mg P per kg soil), and a reference zone (R zone, 26°28′ N, 80°42′ W <500 mg P per kg soil). More detailed description can be found in Qian et al. (2009).

Live and dead cattail leaves were collected from all three zones, while live and dead sawgrass leaves were collected from the M and R zones only because H-zone has monotypic vegetation dominated by cattail. Cattail ash samples were also collected from the H zone during a prescribed fire on 25 July 2006. Briefly, 22 ash collectors (aluminum pans of 30 cm × 40 cm × 6 cm) were installed within the highly-impacted zone (H2 plot in H zone). 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.

Experimental Design

All plant samples collected in the field were separated into 10 subsamples based on the species, whether live or senescent, and locations. 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. All plant samples were burned at five different temperatures (i.e., 150, 250, 350, 450, and 550°C) which can be encountered in field fire (Miao and Carstenn, 2006). Each treatment was triplicated. The following parameters were determined for both oven-dried and muffle furnace burned subsamples: total C (TC) and TN (CNS analyzer, Elementar Analysensysteme GmbH, Germany); TP (EPA 365.1, DU 640 Spectrophotometer, Beckman, Germany); total calcium (TCa), total magnesium (TMg), total potassium (TK) (ICPMS, HP4500 PLUS, Hewlett-Packard Co., Germany); total iron (TFe) and total aluminum (TAl) (AAnalyst 600, PerkinElmer, Shelton, CT); water soluble phosphorus (PO_4–P) (DU 640 Spectrophotometer, Beckman, Germany); as well as ammonia as nitrogen (NH_4–N) (Auto Analyzer 3, Bran Luebbe, Germany). Ash and plant residue pH was measured in a 1:50 dilution with double deionized water (DDI water) using an AR-60 Dual Channel pH/Conductivity meter. Triplicate samples were analyzed and the average was reported for each parameter.

In addition, pH, TN, TC, TP, total metals (Ca, Mg, K, and Fe), water soluble P and ammonia were also determined in the ash samples collected from the field, to compare them with the laboratory simulation results.

Burn Temperature

Discriminant analysis (DA) was conducted to reduce the complexity of the data by identifying significant predictors. Discriminant analysis is a statistical supervised pattern recognition method, which is used to discriminate a priori known groups (e.g., data from different burn temperatures, seasons, regions, etc.) by determining the variables with the most significant mean differences between groups (Statsoft Inc., 1984; Fraley and Raftery, 2002; Insightful Corporation, 2005). Data obtained from the laboratory muffle furnace simulation were separated into four subsets based on species (i.e., cattail and sawgrass) and leaf type (i.e., live or dead leaf) and subjected to DA separately. Each subset was split into five groups based on the burn temperatures (i.e., 150, 250, 350, 450, and 550°C). The temperature group was used as the dependent variable. The predictors (independent variables) initially included in the DA analysis were pH, TN, TC, TP, TMg, TK, TCa, TFe, PO_4–P, and NH_4–N. An F test (Wilks' lambda) was used to test if the discriminant model as a whole was significant, and the individual predictors were then be assessed to see which differ significantly for the mean by group and this was used to classify the dependent variable (burn temperature group) (Insightful Corporation, 2005). A multiple linear regression (MLR) model relating burn temperature to significant predictors was then developed (Insightful Corporation, 2005).

Predicting Nutrient Loss in Field Ash

The data obtained in the laboratory simulation experiments were used to establish predictive models to predict nutrient loss. We combined data of two species (i.e., cattail and sawgrass) to developed predictive models for each parameter due to the similar responding pattern of these two species to the heating and burning. For TN and TC, the losses of TN and TC during combustion were plotted against temperature, and a nonlinear regression was applied to fit the plotted curves. For TP, the ratio of ash TP concentration (AshTP, mg g^{-1} ash) to leaf TP concentration (LeafTP, mg g^{-1} dry leaf) was plotted against temperature and again a nonlinear regression was used to fit the curves to obtain the predictive models. After these predictive models were established, nutrient concentrations in field ash were then estimated following the estimation of the burning temperature in step 1. These predictive models were further verified by comparing the estimated nutrient concentration with the laboratory measured nutrient concentration in the field-collected ash.

Model Development

Postfire TP budget was calculated using the following equation:

$$\text{TPbudget} = \text{Fuelload} \times \%\text{Ash} \times \text{AshTP} \times \text{Burnarea} \qquad [1]$$

where TPbudget is the TP released into ecosystem via ash postfire (mg), Fuelload is the prefire combustible biomass within the burn area (g $(m^2)^{-1}$), %Ash is the percentage of ash production under the estimated burn temperature (obtained from the laboratory simulation), AshTP is the concentration of TP in the ash (mg g^{-1} ash), and Burnarea is the area of the burn site (m^2).

Results and Discussion

Data Characteristics of Laboratory Burned Biomass

In laboratory simulation experiments, it was observed that ash pH, some nutrient and metal contents were strongly dependent on burning temperature (Fig. 1 and 2). Similarly increasing trends in pH along the temperature gradient were observed for both cattail and sawgrass, with an acidic pH at lower temperature and a basic pH at higher 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. 2). This significant increase in pH of the burned plant residues was attributed to basic 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., 2006). Different nutrients and metals showed different patterns of variation corresponding to burning temperature (Fig. 3). The general patterns observed were that TN and TC concentrations decreased with increasing temperature, while TP and metals showed complex variations within the temperature range (150–550°C), which were also observed previously (Marion et al., 1991; Gray and Dighton, 2006). Almost 99% of TN and TC were lost at 450 and 550°C (to concentrations below detection limit) while 30 to 70% of TN and 60 to 90% of TC losses occurred from 150 to 350°C. Unlike TN and TC, TP and metals exhibited slight variations with increasing burn temperature in terms of their dry leaf content, due to their relatively high vaporization points. Detailed information on the characteristics of pH and nutrient and metal contents after combustion at different temperatures can be found in a previous study (Qian et al., 2009). It should be noted that the nutrient and metal concentrations shown in Fig. 4 were calculated based on the dry leaf weight. The nutrient and metal concentrations are expressed as milligrams of nutrient or metal per gram of oven-dried leaf, which were calculated as concentration in ash multiplied by the ash ratio (ash weight divided by original dry leaf weight) following the equation

$$\text{NutrientConc.(mg/gDleaf)} = \text{NutrientConc.(mg/gAsh)} \qquad [2]$$

This is because the ash ratio varied with temperature and thus ash-weight based concentrations would not be indicative of nutrient or metal loss during combustion. Instead, dry leaf weight based concentrations can provide information on nutrient or metal loss due to combustion process.

The close relationship between ash pH, nutrients, metal contents, and burning temperature provided a basis for grouping data based on temperature. Our results suggest that DA is effective in classifying the temperature group and identifying the relative importance of predictors in the classified group. We first included pH, TN, TC, TP, TMg, TK, TCa, TFe, PO_4–P, and NH_4–N as the predictors to group laboratory data and found that of the 45 observations, only one was misclassified by the DA, indicating that the characteristics of ash pH and nutrient and metal distribution along the temperature gradient could be used for grouping. We further reduced the predictors to pH, TC, TP, TK, TCa, and TFe which differed significantly in means by group during the DA analysis and were thus selected as important predictors to discriminate the temperature groups.

Establishment of Predictive Models

Because temperature is important during prescribed fires and the temperature of our prescribed field fire was not mea-

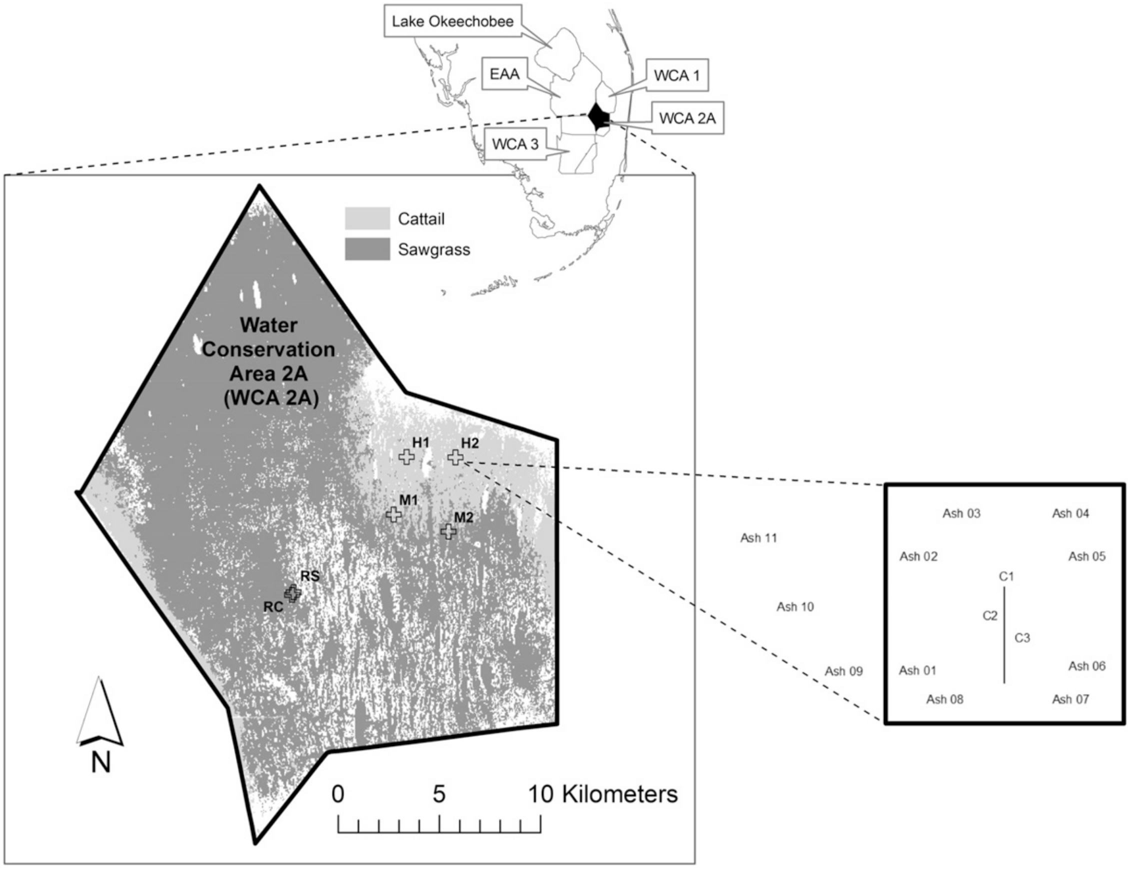

Fig. 1. Sampling location in Water Conservation Area 2A (WCA 2A), northern Everglades, South Florida. Leaf samples of cattail and sawgrass were collected from unburned H1 (highly-impacted zone), M1 (moderately-impacted zone), and RS (reference zone) areas, and ash samples were collected from H2 (highly-impacted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

sured directly, a MLR model was first established to predict the burn temperature of the prescribed fire using the predictors that were obtained from the DA analysis (e.g., pH, TC, TP, TK, TCa, and TFe).

$$T = a0 + b1\log(pH) + b2\log(TC) + b3\log(TP) + b4\log(TK) + b5\log(TCa) + b6\log(TFe) \quad [3]$$

where T is the predicted burn temperature; log(pH), log(TC), log(TP), log(TK), log(TCa), and log(TFe) are log-transformed nutrient concentrations (pH unit for pH, $\mu g\ g^{-1}$ ash for TFe, and $mg\ g^{-1}$ ash for other variables); and a0, b1, b2, b3, b4, b5, and b6 are model parameters. Model parameters were determined by using laboratory data and the results suggested that the MLR model is significant for predicting burn temperature ($r^2 = 0.94$, $P < 0.01$). By inputting the corresponding values determined for field ash into this MLR model, we estimated that the average burn temperature of the prescribed fire in the H2 area on 25 July 2006 was at 395°C. It should be noted that the estimation of an average temperature is limited in characterizing the temperature of field fires. The temperature of prescribed as well as wild fire would vary in different fires, and at different locations within the same fire, depending on weather, vegetation type, amount of fuel load, fuel moisture, and hydrologic conditions at the sites.

During combustion, the loss of N and C vs. material mass followed similar patterns (Fig. 3). The percentage losses of TN (or TC) vs. material mass showed a significant linear correlation in the form of $Y = a \times X$ where Y and X are TN (or TC) and mass

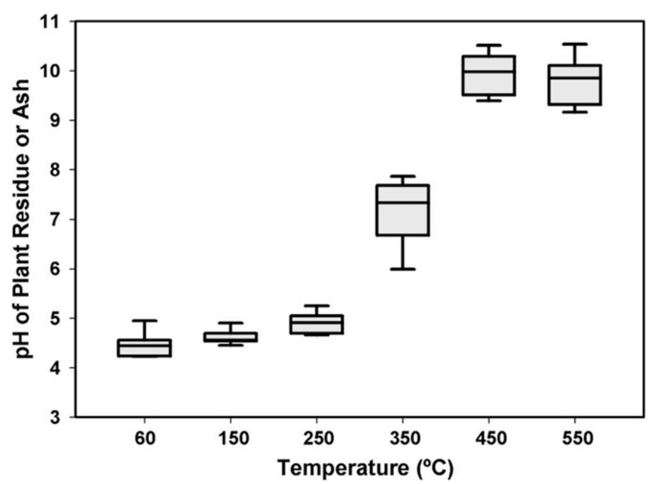

Fig. 2. Variations of pH for plant residue or ash along temperature gradient. Each box includes data for all samples (live and dead leaves of cattail and sawgrass from three nutrient impacted zones, that is, highly-impacted (H), moderately-impacted (M), and reference (*R*) zones) burned at corresponding 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.

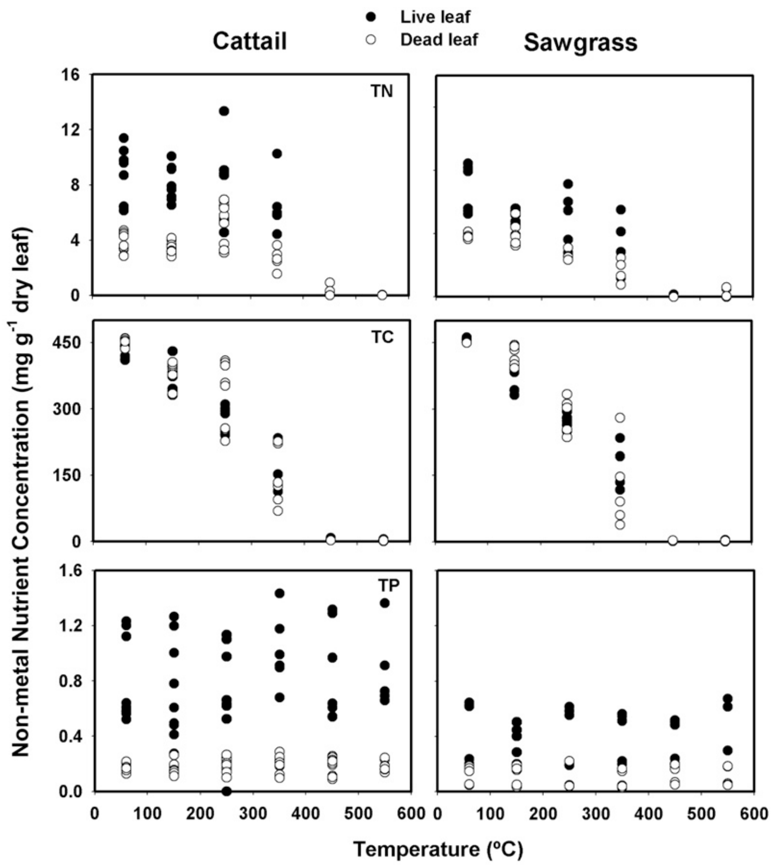

Fig. 3a. Variations of nonmetal nutrient concentrations along temperature gradient. Nutrient concentrations are expressed as per gram of oven-dried leaf, and calculated as concentration in ash multiplied by ash ratio (ash weight divided by original dry leaf weight) under certain temperature: NutrientConc.(mg/gDleaf)=NutrientConc.(mg/gAsh) × Ashratio **.**

loss, respectively. All correlations were significant ($P < 0.01$, see Fig. 4 for detailed information on regression parameters). More importantly, the slopes of these correlations are very close to 1 (0.96 and 0.94), indicating that TN or TC loss occurred predominantly through volatilization during combustion. This is consistent with the low volatilization temperature of N or C and also provides the basis for predicting TN or TC loss during a fire (Raison et al., 1985). Models were also established for predicting mass, TN and TC losses at different temperatures since the three items shared similar patterns in variations with the burning temperature. We selected nonlinear regression over linear regression models because our laboratory data showed apparent deviations from linear relationships between temperature and loss of mass, TN, or TC (Fig. 5). As shown in Table 1, the relationships between temperature and mass, or TN, or TC loss, expressed as $Y = a \times X^{b}$, were strong (with $P < 0.01$).

The loss of TP with increasing temperature during combustion was not as apparent as TN or TC (Fig. 3), but the concentration of TP in ash did change probably due to the slight losses of TP with increasing temperature (Raison et al., 1985; Qian et al., 2009). Therefore, a different model was selected, in comparison to TN and TC, to predicting TP change during combustion. The ratio of ash TP concentration (AshTP, mg g^{-1} ash) to leaf TP concentration (LeafTP, mg g^{-1} dry leaf) was observed to increase with elevated burning temperature (Fig. 6). This ratio can vary from about 1 (for temperature below 200°C) to 20 (for temperature at 550°C). Nonlinear regression to data plotted in Fig. 6 explained a strong relationship between AshTP to LeafTP concentration ratio and burning temperature ($r^2 = 0.73$ and $P < 0.01$) (Table 1). The predictive models in Table 1 included an intercept (y0) to account for particulate TP loss due to fine particles which almost inevitably occurs in field fires.

Comparison of Predicted Data with Laboratory Measured Data for Field-collected Ash

Using the predictive models established above, we estimated ash TN, TC, and TP concentrations during the prescribed fire in the Northern Everglades in 2006 and compared these predicted values with the laboratory measured values to test the accuracy of these predictive models. This prescribed fire was conducted at the H2 site and cattail was the dominant vegetation in this area. It was further observed that during the fire only dead cattail leaves could be burned to form ash. Therefore, the TN, TC, and TP concentrations in dead cattail leaf from the P highly impacted area (H site) were used as the original concentrations in the plants before burning during this prescribed fire. The temperature of the prescribed field fire in the Everglades was estimated to be 395°C according to the MLR model describing the relationship between burning temperature and pH, TC, TP, TK, TCa, and TFe in ash (see Eq. [3]). We then estimated

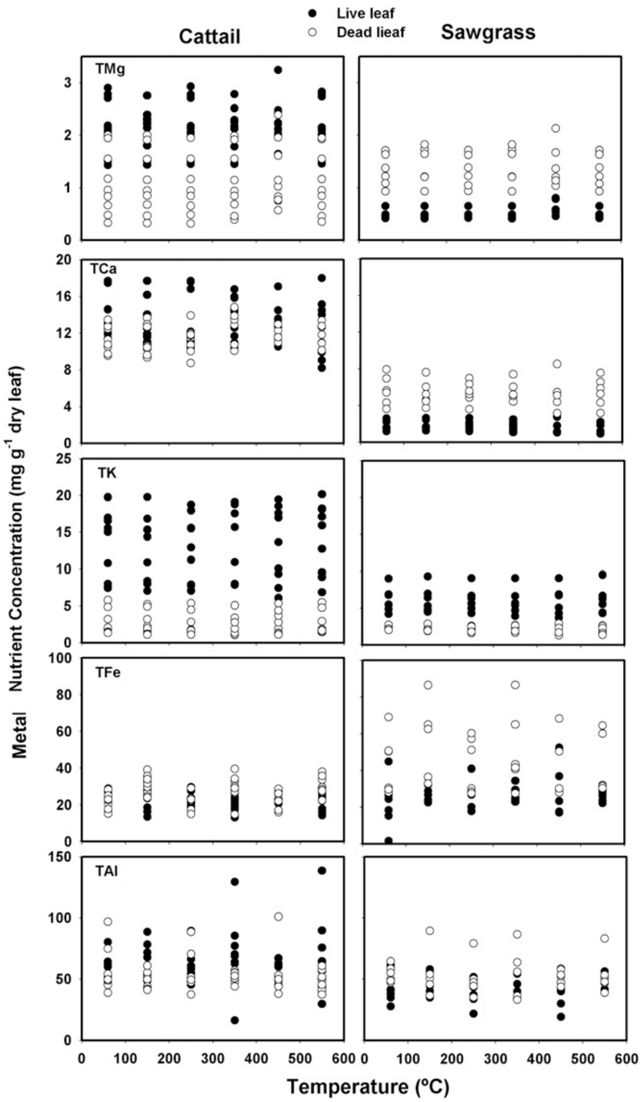

Fig. 3b. Variations of metal nutrient concentrations along temperature gradient. Nutrient concentrations are expressed as per gram of oven-dried leaf, and calculated as concentration in ash multiplied by ash ratio (ash weight divided by original dry leaf weight) under certain temperature:
NutrientConc.(mg/gDleaf)=NutrientConc.(mg/gAsh) × Ashratio .

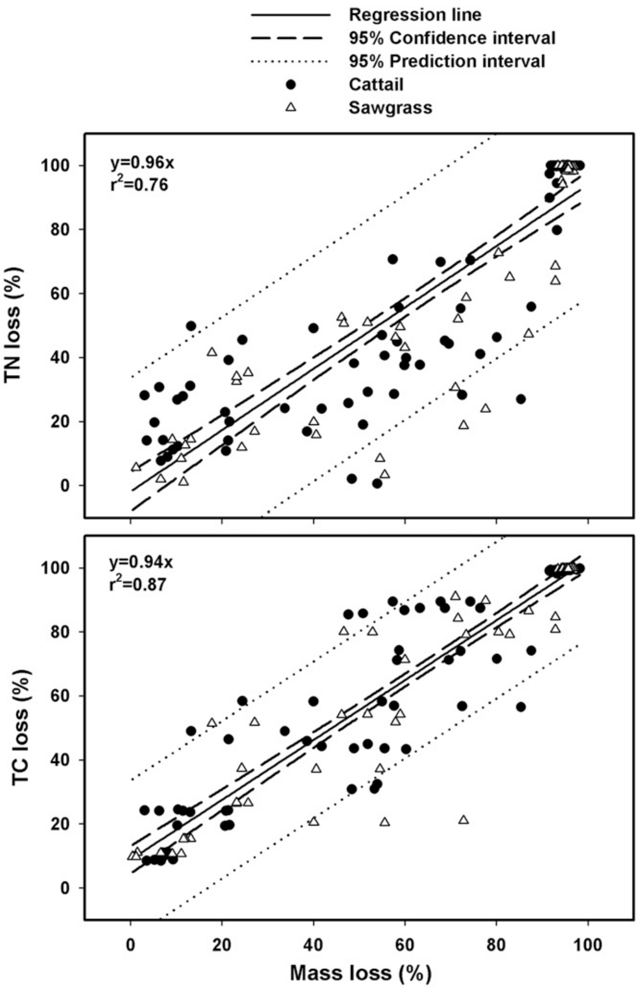

Fig. 4. Linear relationship between mass loss and total nitrogen (TN) and total carbon (TC) loss during cattail and sawgrass combustion in laboratory experiments. Regression lines were built up using all data (i.e., combination of cattail and sawgrass data).

that the mass loss during this fire would be 72.0% while TN and TC losses would be 66.4% (95% confidence interval: 63.6 to 69.3%) and 77.0% (95% confidence interval: 74.7–79.3%), respectively. The AshTP to LeafTP concentration ratio was estimated to be 9.1 (95% confidence interval: 8.0–10.2%). Based on these predicted values, we further calculated the TN, TC, and TP concentrations in ash as 5.45 (95% confidence interval: 4.99 to 5.92), 357 (95% confidence interval: 322–393), and 1.91 (95% confidence interval: 1.68–2.15) mg g^{-1}, respectively.

Comparing the predicted concentrations with the laboratory measured values, it was found that the predicted ash TN concentrations agreed well with the measured values while the predictive TC and TP showed certain deviations from the measured concentrations (Fig. 7). It should be noted that even the measured ash TN, TC, and TP concentrations exhibited very broad ranges (0.78–9.31, 99–435, and 1.00–5.19 mg g^{-1} for TN, TC, and TP, respectively). In consideration of these wide ranges, the potential use of laboratory simulation data in predicting nutrient concentrations in field ashes appeared to be promising. It also should be pointed out that the combustion processes conducted in our laboratory simulations were not identical with those in field fires. In laboratory experiment a muffle furnace does a complete burn and elements are not lost to soil or water. In the field, element loss to soil or water will occur. If further simulated laboratory or controlled field experiments that mimic more closely the prescribed fires are conducted, the data from these experiments will greatly enhance the robustness of the predictive models.

Estimation of Total Phosphorus Budget in the Prescribed Fire

Unlike TN and TC which are lost predominantly through a gaseous volatilization pathway, TP can be lost to the atmosphere through either volatilization (usually very little in field fires due to the relatively high volatilization temperature of P) or the suspension of fine particles (Raison et al., 1985). Total P loss through suspension of fine particles in a typical fire cannot be neglected,

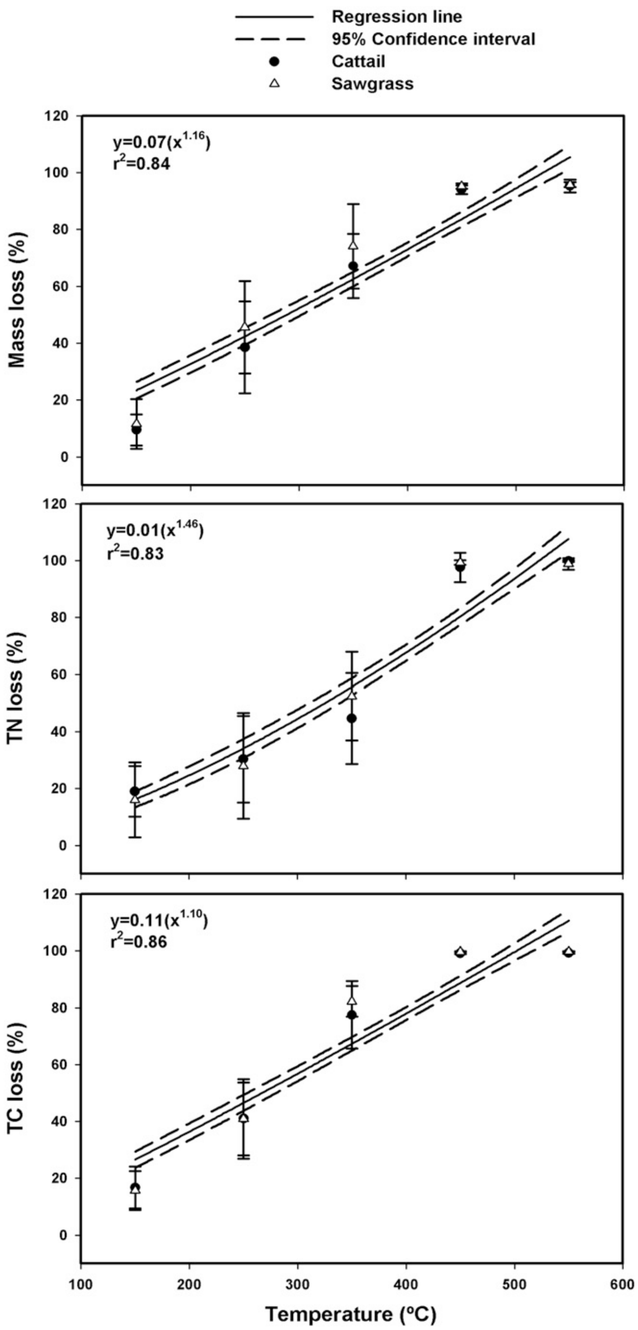

Fig. 5. Mass, total nitrogen (TN), and total carbon (TC) loss as a function of burn temperature during cattail and sawgrass combustion in laboratory experiments. Regression lines were built up using all data (i.e., combination of cattail and sawgrass data).

which is why we included an intercept in the predictive model describing the relationship between AshTP to LeafTP concentration ratio and burning temperature. Therefore, the mass balance for TP should be expressed as: leaf TP content equals ash TP content plus TP loss through particulate suspension, in a prescribed fire. In our prescribed fire, on average the fire burned 1120 g $(m^2)^{-1}$ of dead leaves (78% of total dead leaf mass) and 112 g $(m^2)^{-1}$ of live leaves (mostly just the very tips of the live leaves that were dead and dry). We assumed that these leaves were cattail leaves because cattail is the dominant vegetation in the area. The fire was prescribed in a burning area of 90,000 m^2 (300 by 300 m). Based on the TP model we developed for cattail, we estimated that during this fire, 13.0 kg of TP was released from plant leaves of which 9.5 kg (73.1%) of TP was retained in ash while 3.5 kg (26.9%) was lost to the atmosphere through particulate suspension. These results close to previous study which reported that 21% TP loss during a heathland fire (Niemeyer et al., 2005). Kauffman et al. (1994) studied nutrient loss during the fire along a vegetation gradient in the Brazilian cerrado. The losses of TP from the burning site were 22, 34, 45, and 67% for cerrado sensu stricto, campo cerrado, campo sujo, and campo limpo, respectively. The proportions of the quantity lost as particulates versus that through volatilization varied among plant communities, for example, 88% of P lost as particulates for cerrado sensu stricto, while 18% of particulate loss of P for campo limpo; and for campo cerrado and campo sujo, the particulate loss of P were 58%. Gillon and Rapp (1989) observed that 35% of TP was lost to the atmosphere, with 65% of TP retained in the ash during a scrub forest fire. Raison (1979) estimated that 13 to 20% of TP was transferred to the atmosphere during pasture grasses fires. However, significant losses of P (up to 60% of TP contained in the fuel) were identified for subalpine forests fires, where in excess of 50% of such a loss might be in the nonparticulate form (Raison et al., 1985). Loss of P was much less (2%) during a California chaparral fire (Debano and Conrad 1978).

The capability of estimating P budget of the developed models demonstrated the advantages of these models. For elements that cannot be completely volatilized during the fire (e.g., P), it is important to determine the amount of P lost to atmosphere (probably as particulates) and retained in ash during combustion to evaluate the environmental impact of fires on the surrounding ecosystems. However, it is very difficult to directly measure P loss during a fire (in particular for a wildfire). This portion of P must be calculated by applying appropriate models. The models we developed in this study have the power to do this by estimating the temperature of field fires and subsequently estimating the distribution of P between ash and particulate phase. Although some parameters (e.g., total concentrations of some nutrients in ash) are needed to estimate the temperature, these parameters can be easily measured.

Table 1. Models used to predict mass and nutrient loss (Y) as a function of temperature (X) during fire. Cattail and sawgrass data were combined when developing these models. The predictive models for TP include an intercept (y0) to account for particulate TP loss due to fine particles which almost inevitably occurs in field fires.

	Model	Parameter			r^2	p
		a	b	y0		
Mass loss	$Y = a \times X^b$	0.07	1.16	–	0.84	$P < 0.01$
TN loss	$Y = a \times X^b$	0.01	1.46	–	0.83	$P < 0.01$
TC loss	$Y = a \times X^b$	0.11	1.10	–	0.86	$P < 0.01$
AshTP to LeafTP	$Y = y0 + a \times \exp(b \times X)$	3.25	0.004	−5.96	0.73	$P < 0.01$

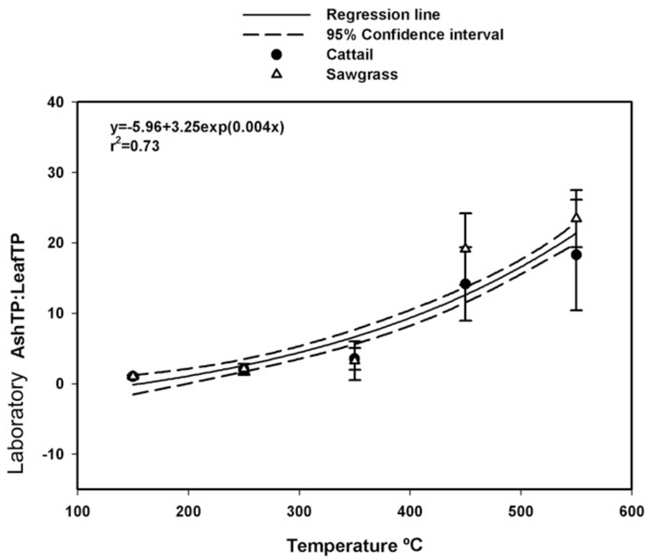

Fig. 6. AshTP to LeafTP concentration ratio as a function of burn temperature during cattail and sawgrass combustion in laboratory experiments. Regression line was built up using all data (i.e., combination of cattail and sawgrass data).

Conclusions

During a prescribed fire, ash pH, nutrient and metal contents were strongly dependent on burning temperature. Our study developed a useful MLR model to predict the burn temperature of the prescribed fire using the predictors that were obtained from the DA analysis (e.g., pH, TC, TP, TK, TCa, and TFe). Nonlinear regression models were established to quantitatively describe relationships between temperature and loss of mass, TN, TC, or AshTP to LeafTP concentration ratio. The potential use of these nonlinear models relating nutrient loss to temperature in predicting nutrient concentrations in field ash were examined by comparing the predicted nutrient concentrations in ash with the laboratory measure values. Results suggested that these nonlinear models are successful to predict postfire ash nutrient loss following the estimation of burning temperature. These models were used to calculate postfire TP distribution in the northern Everglades. The calculation suggested that 73.1% of TP was retained in the ash while 26.9% was lost to the atmosphere, agreeing well with the previously reported distribution of TP during wild fires.

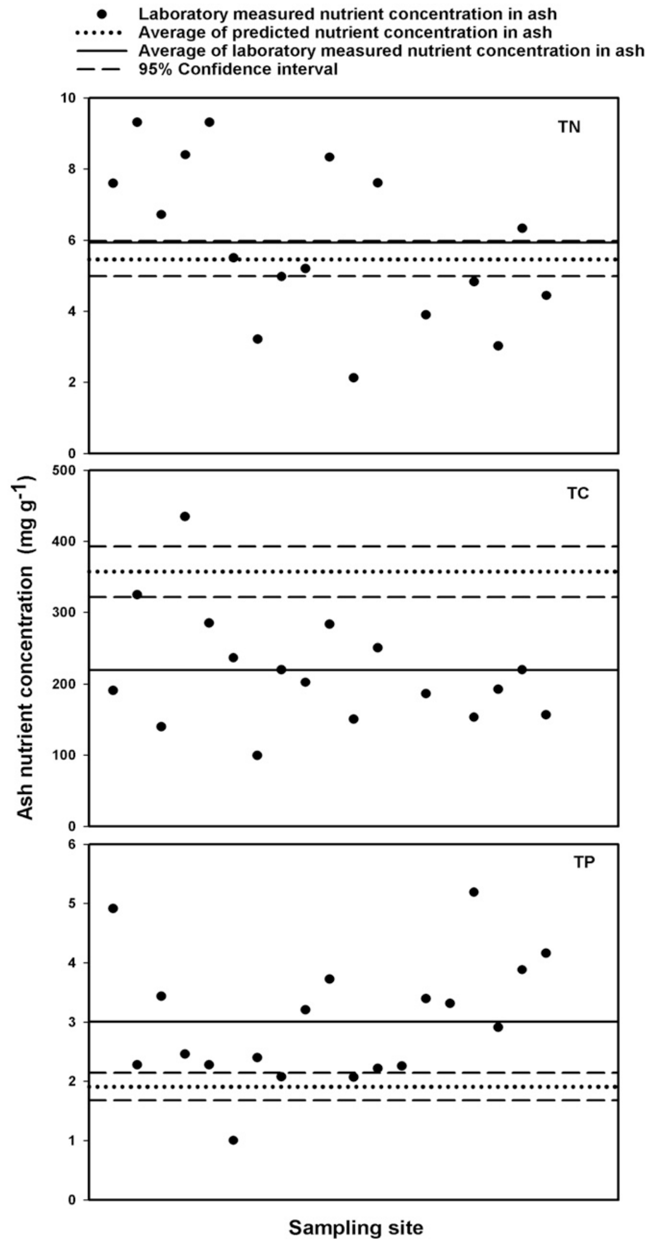

Fig. 7. Comparison between predicted and laboratory measured values for total nitrogen (TN), total carbon (TC), and total phosphorus (TP) concentration in field-collected ash. Laboratory measured data for TN, TC, and TP concentration in field-collected ash samples are plotted against ash sampling sites in highly-impacted zone (H2 area). Values of predicted data for TN, TC, and TP concentrations in field-collected ash were calculated using predictive models at temperature 395°C, which was calculated based on Eq. [3].

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