The Short-Term Effects of Prescribed Burning on Biomass Removal and the Release of Nitrogen and Phosphorus in a Treatment Wetland

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Nutrient removal by constructed wetlands can decline over time due to the accumulation of organic matter. A prescribed burn is one of many management strategies used to remove detritus in macrophyte-dominated systems. We quantified the short-term effects on effluent water quality and the amount of aboveground detritus removed from a prescribed burn event. Surface water outflow concentrations were approximately three times higher for P and 1.5 times higher for total Kjeldhal nitrogen (TKN) following the burn event when compared to the control. The length of time over which the fire effect was significant ($P < 0.05$), 3 d for TKN and up to 23 d for P fractions. Over time, the concentration of soluble reactive phosphorus (SRP) in the effluent decreased, but was compensated with increases in dissolved organic phosphorus (DOP) and particulate phosphorus (PP), such that net total P remained the same. Total aboveground biomass decreased by 68.5% as a result of the burn, however, much of the live vegetation was converted to standing dead material. These results demonstrate that a prescribed burn can significantly decrease the amount of senescent organic matter in a constructed wetland. However, short-term nutrient releases following the burn could increase effluent nutrient concentrations. Therefore, management strategies should include hydraulically isolating the burned area immediately following the burn event to prevent nutrient export.

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Wetland treatment is a common, globally applied, technique to remove nutrients from wastewater before discharge into natural water bodies (Kadlec and Knight, 1996). Wetlands can provide water quality improvement due to several different biotic and abiotic processes. These include high rates of organic matter production (DeLaune and Pezeshki, 2003), microbial activity (D'Angelo and Reddy, 1999), and redox- (White and Reddy, 2001), precipitation-, and sorption reactions (Rhue and Harris, 1999). However, in general, constructed wetlands have a finite lifespan since they accumulate significant quantities of organic matter over time, experience short-circuiting of flow paths (Wang et al., 2006), leading to an eventual decline in treatment efficiency.

There are several potential management strategies to deal with organic matter accumulations which can negatively affect treatment performance, including dredging of the accumulated organic matter (Wang et al., 2006), addition of chemical amendments (Malecki-Brown et al., 2007) to lock up released nutrients, and prescribed burns of the organic detritus. Dredging of material can significantly disrupt operations of the wetland, as it requires a drawdown of surface water for long periods, physical removal of material, disposal, and revegetation before use. Chemical amendments, primarily alum, have been used in lakes (Cooke et al., 1993) to remove P and several Al-containing amendments were recently evaluated for use in a constructed wetland to improve P sequestration (Malecki-Brown et al., 2007). These amendments have the ability to remove P from the water column and also to intercept P that is released from the soil but can alter the pH of the system (Malecki et al., 2004). A prescribed burn is one strategy which has not been evaluated with respect to quantification of the removal of organic detritus and short-term resultant water quality implications for constructed wetland systems.

Prescribed burns have been used to control invasive species (Ditomaso et al., 2006), enhance community richness and diversity (Kost and De Steven, 2000), reintroduce the natural burn cycle (Loveless, 1959), and promote the success of particular

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Abbreviations: DOP, dissolved organic phosphorus; OEW, Orlando Easterly Wetland; PP, particulate phosphorus; SRP, soluble reactive phosphorus; TDP, total dissolved, phosphorus; TP, total phosphorus; TKN, total Kjeldhal nitrogen.

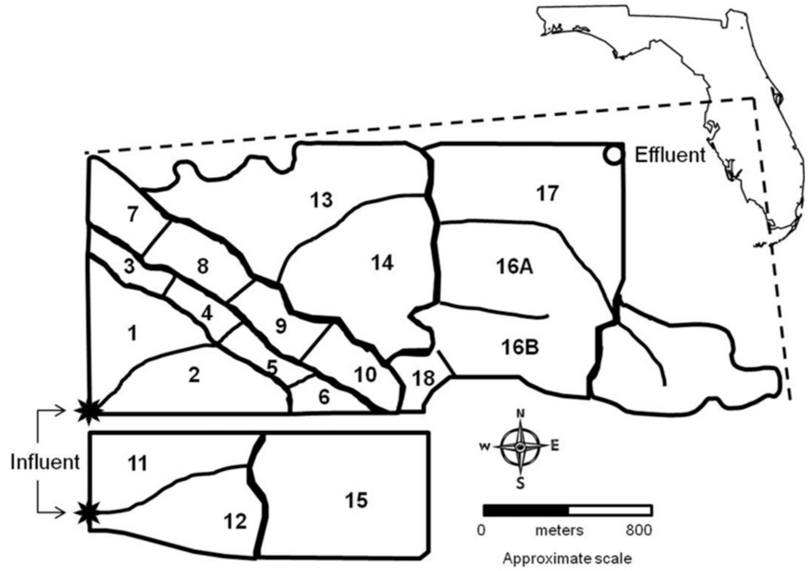

Fig. 1. Plan view of the Orlando easterly municipal wastewater treatment wetland in Christmas, FL. Surface water flows from influent points across the wetland to the northeast discharge point. Experimental units were cells 8 (burn) and 9 (control).

plant species that are rare, endangered, or vital to wildlife (Kirkman et al., 2000; Norton and DeLange, 2003). In wetlands, fire can be an important ecological forcing function in the southeastern United States (Cypert, 1961; Frost, 1995).

Several studies have investigated the impact of fire on water quality at the watershed level, producing highly variable results. In general, the main effect of fire is to remove biomass and mineralize nutrients (Lugo, 1995). Burned areas may be more susceptible to erosion in watersheds that experience precipitation events soon after a burn and may have increased fluxes of particulate P in their streams (Prepas et al., 2003). Nitrogen fluxes are also possible because of the high solubility of nitrate (Neary et al., 2005). However, Clinton et al. (2003) and Richter (1982) found small or no increases in stream N concentrations following fire.

Most studies addressing the effect of fire events in wetlands occurred in natural systems and focused on the alteration in species composition or soil properties, rather than water quality. Fire can promote primary production in wetlands by increasing the availability of nutrients and reducing competition (Norton and DeLange, 2003). Although increases in wetland species richness, diversity, and cover have been recorded following fire, the effects are normally short-lived, returning to preburn conditions in as little as one growing season (Kost and DeSteven, 2000; Norton and DeLange, 2003; Willard et al., 1995). Significant quantities of organic C are volatilized during a wetland fire (Dikici and Yilmaz, 2006; Smith et al., 2001) suggesting an effective method for removal of organic matter detritus. High concentrations of cations in ash can increase soil pH (Dikici and Yilmaz, 2006; Neary et al., 2005). Volatilization of N has been shown to be a significant vector for N loss in peat soil burns (Smith et al., 2001). Fire can also increase total N through accelerated rates of mineralization (Hobbs and Schimel, 1984; Kutiel and Shaviv, 1992; Wilbur and Christensen, 1983) and increased rates of nitrification–denitrification have also been documented following fire (Neary et al., 1999).

The majority of P in a wetland is unavailable because it is assimilated in organic matter or associated with other elements (e.g., Ca, Fe, Al, Mg). Combustion of organic matter has been shown to increase TP, especially the proportion of bioavailable P (Smith et al., 2001; Wilbur and Christensen, 1983; Faulkner and Delacruz, 1982), however, another study indicated no change in P concentration following fire (Dikici and Yilmaz, 2006).

The effect of fire on constructed wetland systems has been given little attention in the literature. If prescribed burns are used as a management tool in treatment wetlands, it is important to understand the impact on the water quality function of the wetland as well as the potential for removal of organic detritus. The goal of this study was therefore to quantify the short-term effects of a prescribed burn on the storage of aboveground detrital material and resultant water quality. The objectives were to quantify: (i) changes in aqueous N and P concentrations in the water column after the burn, (ii) the length of time the water quality is impacted by the burn, and (iii) the short-term reduction of aboveground biomass.

Methods and Materials

Site Description

The study was conducted at the Orlando Easterly Wetland (OEW), a large municipal wastewater treatment wetland near Christmas, FL (Fig. 1). The purpose of the OEW is to polish advanced secondary treated wastewater from the City of Orlando by reducing the concentration of N and P before discharge to the St. Johns River (Post, Buckley, Schuh and Jernigan, 1993). The treatment wetland was built as a series of 18 interconnected cells of varying size (Wang and Jawitz, 2006). Since the OEW began operation in 1987, the system consistently demonstrated discharge concentrations of N and P below the required limits of 2.31 and 0.2 mg L^{-1}, respectively (PBS&J, 1993). However, recent spikes in winter discharge concentration have led manag-

Table 1. Select morphological and soil characteristics of the paired cells used in the study.

	Burn cell	Control cell
Cell area (m^2)†	121,000	109,000
Cell volume (m^3)†	29,700	32,400
Vegetation‡	*Typha*-dominated	*Typha*-dominated
pH‡	6.8 ± 0.2	6.9 ± 0.4
OM Content (%)‡	18.8 ± 10.6	14.8 ± 12.2
Total C (g kg^{-1}) ‡	94.9 ± 53.6	67.7 ± 59.5

† Data after Martinez and Wise (2003).

‡ Data after Miner (2001).

ers to explore rejuvenation methods (Malecki-Brown et al., 2007; Wang et al., 2006). Many of the OEW cells were found to be hydraulic inefficient (Martinez and Wise, 2003), likely due to organic matter accumulation over the years. Reduced residence time caused by short-circuiting is one factor responsible for lower nutrient removal rates and directing flow into channels rather than desired sheet flow (Wang et al., 2006). Cells 8 and 9 were chosen as field duplicates because of the similarity in physical characteristics, soil and plant composition, and identical location along the surface water flow path (Table 1). Both cells received inflow from the same cell, each drained from a single outflow, and both received the same hydraulic load.

Experimental Manipulation

Wetland cell 8 underwent a controlled burn on 7 Oct. 2001 while wetland cell 9 served as an unburned control. Both cells received surface water through a single split culvert draining from cell 4 (Fig. 1). The inlet culvert was closed 2 d before the fire to allow the surface water to drain, maximizing the amount of organic material exposed to the fire. The burn was initiated using a kerosene drip along the edge of cell 8 and carried across the cell within 2 h. One day after the fire, the inflow culvert was opened for both wetland cells. Two days after the fire, exit culverts for both cells were opened to re-establish flow.

Field Sample Collection

Surface water grab samples were collected at the inflow and outflow culverts for both the control and burned wetland cells. Filtered and unfiltered water samples were collected on seven dates before the burn (21, 22, 23, 27, 28 Aug.; 12 and 20 Sept., 2001) and on 12 dates following the burn (9, 10, 15, 24, 30 Oct.; 8, 13, 20, 28 Nov.; 6, 13, and 18 Dec. 2001). For simplicity, the burn event has been designated as Day 0, while preburn collection dates are signified by Days –47 to –1 and postburn collection dates are signified by Days 1 to 72.

Aboveground biomass samples were collected by random selection of 13 plots within both wetland cells where all aboveground growth within a 1 m^2 quadrat was collected. Material was stored in plastic bags and placed on ice for transport back to the lab. Each plot was revisited within 2 d following the burn and a second 1 m^2 sample was collected to determine change in biomass.

Laboratory Analyses

Filtered water samples were analyzed colorimetrically for soluble reactive phosphorus (SRP) within 48 h (USEPA, 1993; Method 365.1). In addition, filtered and unfiltered samples were digested and analyzed colorimetrically for total dissolved phosphorus (TDP) and total phosphorus (TP) (USEPA, 1993; Method 365.1). Total kjeldahl nitrogen was also analyzed using the general digestion method outlined by Bremner and Mulvaney (1982) and measured colorimetrically (USEPA, 1993; Method 351.2). Using these three constituents of P (SRP, TDP, and TP), we also calculated dissolved organic P (DOP = TDP – SRP) and particulate P (PP = TP – TDP). Vegetation samples were separated into live and dead material, dried at 60°C until constant weight, and each fraction was weighed.

Statistical Analyses

An additive approach was used to obtain a statistical model of the fire effects on water quality. The objective here is to estimate the duration of the response to the fire event in the water quality, that is, for how long are the nutrient levels in the outflow larger than the background levels. This method also allows us to estimate the magnitude of the response to the fire event, that is, what is the average concentration of a nutrient during the response period to the fire event.

The first variance component chosen consisted of the time-dependent variation obtained from the two cell inputs, which were assumed to be replicate measurements of the same input variable. The best fit was obtained for the antedependence model of order 1. Other models considered were antedependence model of order 2 and a power model. The antedependence model is a generalization of the autoregressive model. An intervention term for the fire effect (df = 1) was applied. The intervention term serves as a dummy variable that estimates the possible effect of the fire event. Since this was a singular event of which the duration of the effect was indeterminate, we estimated the duration of the effect conservatively, allowing it to continue until the end of the sample collection. We included a "cell" term (df = 1) which can be approximated based on the assumption that the effect of the fire is additive on the cell output values. Wald tests were used to determine the significance of the fixed model terms as they were added to the model. This approach does not estimate any interactions.

The fire effects and differences between cells were estimated based on repeated measurements and do not constitute true replication. The data was fitted using repeated measures in a mixed procedure (SAS Institute, 2001). From this procedure, a standard error for the differences (SED) was obtained for the comparison of interest (burn and control) as well as the associated least squares differences (LSD) computed at the 5% error level. The data was examined for normality and homogeneity of variance. Data on vegetation were tested with a one-way ANOVA.

Results

Water Quality

We did not find significant variation in soluble reactive P between cells preburn, suggesting the cells could be considered replicates. We estimated that the fire resulted in significantly higher outflow concentration of SRP in the burn cell, com-

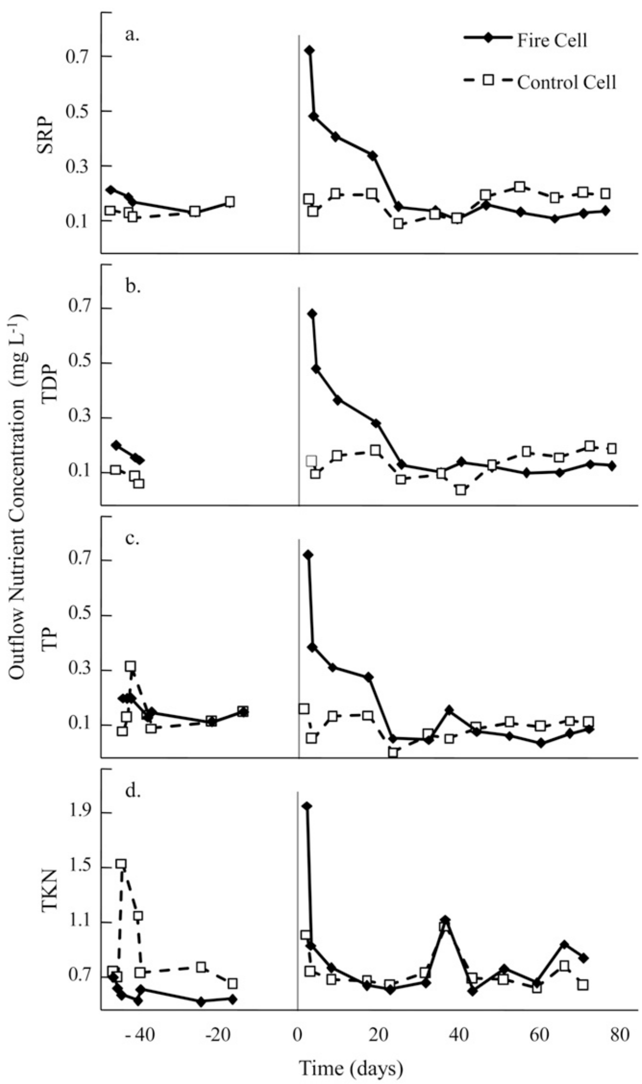

Fig. 2. Nutrient concentrations at the outflow of the burn cell (solid line) and control cell (dashed line) over time for (a) soluble reactive phosphorus (SRP), (b) total dissolved phosphorus (TDP), (c) total phosphorus (TP) and (d) total Kjeldahl nitrogen (TKN).

pared to the control, for an event period estimated at 23 d following the fire. On Days 0 to 23, the fire effect on SRP was significant at LSD 0.056, SED 0.028 (Fig. 2a; Table 2). During the period of observed significant fire effect, the mean outflow concentration of SRP was estimated at 0.397 mg P L^{-1}(Table 2). This is more than three times higher than the SRP concentration of the control cell outflow (0.121 mg P L^{-1}) during the same time period (Days 0–23). There is therefore evidence that there was a time dependent release of SRP as a result of the fire.

In a similar fashion, we observed significantly higher concentrations of outflow TDP and TP in the burn cell, compared to the control cell, and estimated this period to be for the first 17 d after the burn (Table 2). No significant cell effect was observed preburn.

The SED and LSD for TDP were 0.031 and 0.061, respectively, and 0.024 and 0.047 for TP (Table 2). The mean outflow of TDP for Days 0 to 17 was estimated at 0.462 mg P L^{-1} for the burn cell and 0.148 mg P L^{-1} for the control cell (Fig. 2b). Mean outflow TP was three times higher in the burn cell

Table 2. Nutrient data from the fire effect period (i.e., the number of days in which the outflow concentration of the burn cell was significantly higher than the control cell). Mean data represent estimates of the population from the antedependence model.

Nutrient	Length of effect	SED†	LSD	Burn cell mean	Control cell mean
	d			mg L^{-1}	
SRP	23	0.028	0.056	0.397	0.121
TDP	17	0.031	0.061	0.462	0.148
TP	17	0.024	0.047	0.477	0.156
TKN	3	0.061	0.120	1.51	0.95

† SED = standard error of differences, LSD = least squares differences, SRP, soluble reactive phosphorus, TDP, total dissolved phosphorus, TP, total phosphorus, TKN, total Kjeldahl nitrogen.

(0.477 mg P L^{-1}) than in the control cell (0.156 mg P L^{-1}) during the period of significant fire effect (Day 0–17; Fig. 2c). After Day 17, TDP and TP outflow concentrations were not significantly different between the burn and control cells.

We also estimated a significantly higher outflow concentration of TKN as a result of the fire in the burn cell, when this is compared to the control cell. However, the fire effect on TKN was estimated for a much shorter time-span than for P, with elevated TKN releases from the burn cell on Days 0 to 3 only (SED = 0.061 and LSD = 0.120) (Fig. 2d; Table 2). The mean concentration of TKN at the outflow of the burn cell during the first 3 d postburn was estimated at 1.51 mg N L^{-1}, while the mean TKN of the control cell was 0.95 mg N L^{-1} for the same time period.

Before the burn, the average value of TP was estimated 0.157 mg L^{-1}, and consisted almost entirely (97%) of SRP in the burn cell (Table 3). For the first 17 d following the fire, (the period in which the fire effect was observed for TP) mean TP increased to 0.479 mg L^{-1}. However, the relative quantities of the dissolved and particulate constituents remained nearly the same in the burn cell. This suggests the immediate effect of the fire was a release in SRP. Interestingly, after Day 17, TP concentrations in the burn cell returned to preburn levels, but the composition of TP changed. The proportion of SRP decreased to 63%, while the proportions of DOP and PP increased to 18 and 19%, respectively (Table 3). In the control cell, the proportions of SRP, DOP, and PP remained relatively similar throughout the experiment (Table 3).

Aboveground Biomass

Aboveground biomass in the fire cell averaged 195 ± 34.9 g dry wt. m^{-2} of live material and 275 ± 57.5 g dry wt. m^{-2} of dead material before the burn, for a total aboveground biomass of 470 ± 83.7 dry wt. m^{-2} (Fig. 3). Two days after the fire, the average biomass for live material was 18 ± 1.49 g dry wt m^{-2}, and 148 ± 23.1 g dry wt. m^{-2} for dead material (Fig. 3). The total aboveground biomass (live + dead) decreased by 68.5% following the burn. Due to the fire, essentially all the dead material was combusted and almost all the live material was converted to dead material. Consequently, the amount of detrital (dead) material postburn was approximately one-half the amount before the burn. In this wetland, the postburn species composition immediately returned to a *Typha*-dominated community.

Table 3. Soluble reactive phosphorus (SRP), dissolved organic phosphorus (DOP) and particulate phosphorus (PP) mean concentration and percent of total phosphorus (TP). Measurements made at the outflow of the burn and control cells before the prescribed burn (preburn), during the period when the burn cell had significantly elevated TP (fire effect), and after the burn cell TP returned to per-burn levels (postburn). Data represent calculated means from water quality analyses.

Time	Cell	TP =	SRP	+ DOP	+ PP
		mg L^{-1}	———	mg L^{-1} % TP	———
Preburn	Burn	0.157	0.153	b.d.†	0.007
(Day −47 to −1)			97%	0%	3%
	Control	0.136	0.098	b.d.	0.038
			72%	0%	28%
Fire effect	Burn	0.479	0.453	0.007	0.019
(Day 0–17)			95%	1%	4%
	Control	0.184	0.142	0.005	0.037
			77%	3%	20%
Post-burn	Burn	0.155	0.099	0.029	0.031
(Day 18–72)			63%	18%	19%
	Control	0.161	0.130	0.008	0.023
			81%	5%	14%

† b.d. = below detection.

Discussion

The nutrient concentrations in the outflows from the two cells in the period before the burn were not found to be significantly different. This result allows us to approximate the two cells as treatment and control, and estimate the magnitude and duration of the effect of the fire event. All the nutrients concentrations we measured increased in the treatment cell outflow as a result of the fire event. While there was a consistent fire effect, the length of the effect we estimated varied according to the nutrient measured. In general, the period of nutrient release due to the fire was longer for P when we compare this to N. This may be a result of the volatilization of N, which can begin at temperatures of 200° C, whereas P requires temperatures more than 700° C for volatilization (Ditomaso et al., 2006). Also, N has more potential removal that can lead to complete removal of N from a system (White and Reddy, 1999, 2003), whereas P may be continuously cycled between organic and inorganic forms without a dominant gas phase for removal.

Since the OEW received advanced secondarily treated wastewater, SRP was the dominate form of TP before the burn. Seventeen days after burn, outflow water TP concentration returned to preburn levels, but the relative proportions of DOP and PP making up the P pool had increased (Table 3). This may be explained by the live biomass converted to dead biomass as a result of the fire. As the plant structure breaks down and decomposes, the less available forms of P, DOP and PP, may be released from the biomass residue. A similar effect has been seen in wetlands experiencing extended periods of surface water drawdown, which stimulated decomposition, and, on reflood, increased DOP and PP in the water column (Bostic and White, 2007; White et al., 2004; 2006). Meanwhile, the decrease in relative proportion of SRP may be a result of assimilation during the rapid plant growth phase that immediately follows a burn (Loveless, 1959). As a consequence of the burn, much of the P released downstream is in less bioavailable forms (i.e., DOP and PP). The suggestion that a burn event may cause downstream algal blooms seems less likely.

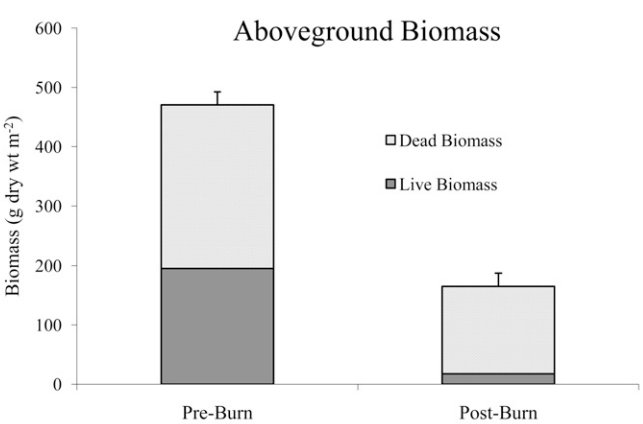

Fig. 3. Live and dead aboveground biomass collected from the burned treatment cell of the Orlando easterly wetland. Postburn data was collected 2 d after the prescribed burn.

As far as we are aware, this study is the first to document a short-term spike in the release of water borne N and P following a prescribed burn in a treatment wetland. The fire effect was evident up to 23 d postburn, suggesting that a good management practice may be to hydraulically isolate the burned area for a period of about a month following the fire. This study did not find an increase in the TP removal capacity of the wetland cell over the short-term (preburn TP effluent averaged 0.157 mg P L^{-1}, and post fire effect TP effluent averaged 0.155 mg P L^{-1}). The relative decrease in the proportion of SRP in TP postburn may mitigate damage to P limited ecosystems downstream at risk of eutrophication, but the continued loss of TP in burn cell through effluent may be problematic for wetland managers seeking to meet nutrient discharge limits for permitting purposes. In the case of the OEW, the additional wetland treatment cells downstream were able to remove the released TP. A prescribed burn in a treatment cell which discharges directly into the natural environment would not be recommended unless it can be temporarily isolated hydraulically, or temporary relief is obtained from permit restrictions.

The most obvious benefit of using a prescribed burn in a treatment wetland is a decrease in the quantity of both live plant biomass and detrital material. There was a 68.5% reduction in total aboveground biomass as a result of the fire, including a >50% reduction in the detrital material. Standing dead plant material is an impediment to surface water flow due to frictional forces. We can assume this substantial loss of biomass decreased flow obstruction in the cell and increased the hydraulic efficiency. By allowing for sheet-flow and longer water residence time (Wang et al., 2006), the burn is expected to increase P removal efficiency in the long-term due to increased primary productivity, however that is beyond the scope of this study.

Conclusion

Prescribed burning is an effective tool for decreasing aboveground biomass in a wetland. Short-term increases in N and P release should be expected and managed for by isolating the burned area following the fire. This would prevent these nutrients from being discharged downstream. The release period of P from the burned wetland is generally longer than the release of N. While the relative proportion of SRP in the effluent of the burned cell decreased following the fire, the net concentration of TP was unchanged in the short-term due to an increase in DOP and PP. The substantial decrease in biomass and detrital matter is expected to increase hydraulic efficiency and encourage sheet-flow in the wetland. By providing more surface area for the assimilation and removal of N and P, the burn may improve nutrient removal in the long term. Future studies should investigate changes in biomass accumulation and nutrient removal efficiency over one or more growing seasons following a prescribed burn. Overall, the prescribed burn appears to be a simple and cost effective method for removing detrital material to prevent the loss of hydraulic efficiency.

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