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# Immediate ecological impacts of a prescribed fire on a cattail-dominated wetland in Florida Everglades

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With 6 figures and 5 tables

**Abstract:** The effects of fire on nutrient release in wetlands prior to, during and afterwards are notably rare. We initiated a long-term and large-scale ecosystem study, driven by a large restoration program, to assess ecological effects of repeated fires on a nutrient-enriched, cattail-dominated wetland in the Florida Everglades. Here, we report the immediate and short-term (30 days) impacts of the first prescribed fire focusing on a central question of whether the fire affected surface-and pore-water nutrient concentrations and forms. Specifically, we addressed several questions: 1) how fast could the impacts be detected, 2) what were the magnitude and duration of the impacts, and 3) were there any downstream effects detected and if so, how far downstream was the impact observed? The results showed that post-fire increases of average surface water total phosphorus (TP) concentrations over 10 days were 128 %, 119 %, and 135 % for within burned plot, 25 m downstream, and 100 m downstream, respectively, relative to the upstream control ($82 \pm 11$ µg $L^{-1}$). A post-fire surface water pH peak (8.4) was observed as soon as 15 minutes after the fire reached within burned plot, and the increase in pH lasted at least three weeks. A significant increase (400 %) in the daily peak dissolved oxygen was detected by the third week post-fire. Daily maximum water temperature increased 2–4 °C post-fire and this increase lasted the duration of the 30-day sampling period. Average periphyton TP concentrations from samples collected within burned plot were $3495 \pm 320$ mg $kg^{-1}$ one month post-fire, but decreased to $1730 \pm 219$ mg $kg^{-1}$ three months post-fire. Cattail seed germination decreased (41 %) from pre- to post-fire, while seed germination of sawgrass and other species increased (97 % and 12 %, respectively). Overall, whether these short-term responses have sustained effects and how they will shape other entities of the ecosystem in the long-term are currently being investigated and will be assessed in the near future.

**Key words:** Surface water, pore water, total phosphorus, TDP, TDKN, DIC, periphyton, seed germination.

## Introduction

Fire is a common natural driving force in a variety of ecosystems, including forests, grasslands, and wetlands. Since the 1970s, fire has been increasingly selected as a tool for ecosystem management and restoration (Wan et al. 2001). Numerous studies have described the effects of fire on nutrients, soil, vegetation, and food webs within the burned terrestrial ecosystem or adjacent aquatic ecosystems (Allen et al. 2003, Cromack et al. 2000, Earl & Blinn 2003, Lamb et al. 2003, Spencer et al. 2003). However, many of these studies focused on isolated changes in ecosystem characteristics resulting from fire, rather than the role of fire in ecosystem processes and functions (Gresswell 1999, Minshall et al. 1989, Minshall et al. 2004) and the linkages among ecosystem processes. For example, in wetlands, ash dissolution in the

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water column as a result of fire can generate a series of ecosystem events including nutrient downstream transportation, nutrient flux from surface- to pore-water, nutrient uptake by plants, or a combination of these mechanisms determining the ultimate fate of the nutrients. Moreover, assessing the effects of water-borne nutrient transport, including the duration and distance downstream of potential impacts, is critical to understanding fire effects in wetland ecosystems. Yet, the extent of fire effects on downstream habitat in wetland systems is largely unknown (Bowman et al. 2009).

The powerful and instantaneous features of fire directly and indirectly affect ecosystems at temporal scales ranging from days to decades (Minshall et al. 2004). Many direct effects of fire that occur during or immediately after the fire are pulsed (Earl & Blinn 2003). Ecosystem responses to pulsed events can be either short-term or sustained. Linking short-term fire effects to long-term ecosystem function (Cromack et al. 2000, Spencer et al. 2003) is important, yet difficult, largely due to the lack of studies focused on ecosystem responses immediately following fire (within hours). The paucity of data describing short-term fire effects is largely due to remote locations, spontaneity of wildfires and the inability to access the site to collect data immediately following the fire.

The Everglades ecosystem in Florida, USA, has experienced increasing anthropogenic influences during the past 100 years. Nutrient enrichment and hydrological alterations have resulted in the replacement of native sawgrass (*Cladium jamaicense* Crantz) by cattail (*Typha* spp.) in highly-impacted areas. In recent years, best management practices and constructed wetlands have been applied to removal of total phosphorus (TP) from the Everglades agricultural area runoff to reduce the impacts to the Everglades Protection Area. Other management alternatives have also been investigated to accelerate the recovery process of the impacted wetlands. One of these potential alternatives is the use of multiple prescribed fires to eliminate cattail biomass since fire is a natural phenomenon that has contributed to the shaping of the historical Everglades landscape (Miao & Carstenn 2006, Miao et al. 2009). Here we report the immediate effects of a prescribed fire on the cattail wetland and asked the following questions: 1) which surface and pore water nutrient concentrations and forms would respond to fire, 2) how rapidly would the nutrients respond, 3) what would be the magnitude and duration of the responses and 4) would there be any downstream effects, and if so, how far downstream was the impact detected? We report the immediate (within 30 days) ecosystem responses to a prescribed fire in a highly nutrient-enriched cattail-dominated wetland.

## Methods

### Area studied and prescribed fire treatment

This study is part of the Fire Project, a long-term ecosystem scale project focusing primarily on the ecological effects of repeated prescribed fires on wetland ecosystem restoration (Miao et. al 2009). The Fire Project was conducted in Water Conservation Area 2A (WCA 2A), a 447 km$^2$ freshwater marsh with a distinct nutrient and vegetation gradient from the northern highly phosphorus (P)-impacted area dominated by cattail (*Typha* spp.) and interspersed with Carolina willow (*Salix caroliniana*) to the moderately P-impacted area containing a sawgrass (*Cladium jamaicense*)-cattail mixture transitioning to the southern reference region, consisting of a sawgrass ridge and slough vegetative community (King et al. 2004). The Fire Project uses a Before-After-Control-Impact-Paired-Series (BACIPS) design (Miao & Carstenn 2006, Miao et al. 2009) initiated in July of 2005. This study focused on a 9-hectare plot (300 × 300 m$^2$) located in the highly nutrient-enriched and cattail-dominated area. Three sampling stations were placed within the plot, one 25 m north and upstream of the plot, and two, 25 m and 100 m south and downstream of the plot (Fig. 1). The upstream sampling station was used as a control for this study.

The prescribed fire was ignited by Florida Fish and Wildlife Conservation Commission on July 25, 2006 by lighting all four sides of the plot and allowing the fire to burn towards the center of the plot. Winds were light out of the southeast; smoke lifted vertically before drifting to the northwest away from the control plot. Average water depth within the burned plot was approximately 11 cm. The plot was accessible for field sampling about three hours after the fire. Water movement within the burned plot was from the north to the south-south west during the three-week sampling period.

### Ash collection and nutrient analysis

Twenty-six ash collectors (30 cm × 40 cm × 6 cm aluminum collecting pans) were installed at the treatment plot, 22 within the plot and four located from 25 to 150 m outside of and northwest of the plot. Two collectors were installed within burned plot sampling stations. One pan was installed just above the surface of the water, under a thick mat of senesced leaves and the second was installed approximately 2 m above the peat surface. The location of the collectors was offset such that the upper collector did not interfere with ash entering the lower collector. Only above canopy collectors were installed outside the plots to collect ash distributed by wind.

Within 30 min of the prescribed fire when flames were no longer visible the ash was carefully brushed from the ash collectors with a thin, fine brush into wide mouth plastic jars. The samples were stored in the dark for 1 month at room temperature until nutrient analyses were performed. The ash samples were analyzed for total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), total carbon (TC), ammonium ($NH_4^+$), nitrite and nitrate (NOx), calcium (Ca), and pH following standard methods (APHA 1998). To quantify total P

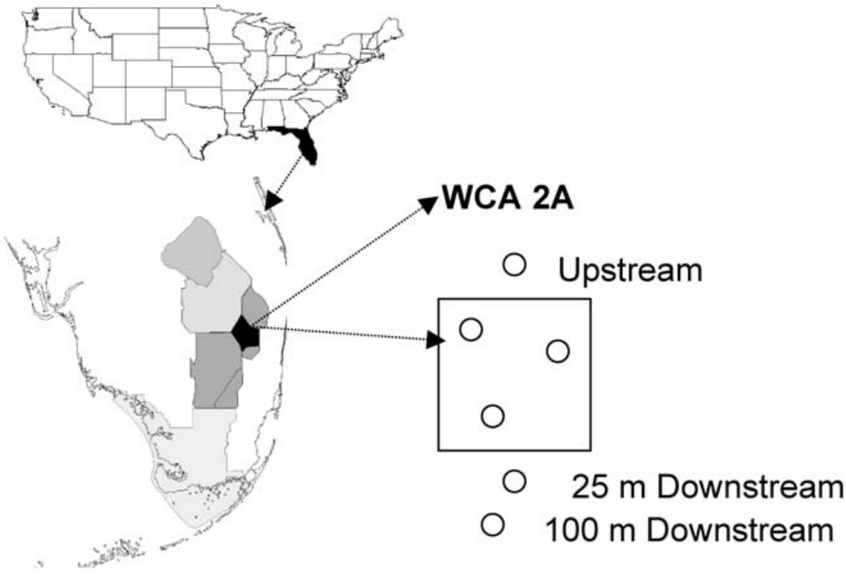


**Fig. 1.** The study area in Water Conservation Area 2A (WCA 2A) of the Everglades. The burned plot was 300 × 300 m$^2$ in area with one upstream (25 m north), three within, and two downstream (25 and 100 m, respectively) sampling stations.

(TP) and total metals, field-collection samples were dry-ashed at 550 °C for 4 h, then dissolved in 2 ml of 6N 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). Total C and N 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), $Ca^{2+}$, ash samples were extracted with 20 ml of DDI water for 2 h, followed by centrifugation (1,789 × g, 15 min) and filtration (0.45 µm MAGNA Micron membrane). A summary of analytical methods was presented in Qian et al. (2009).

## Ecosystem parameters studied

Surface and pore water, temperature, periphyton and soil seed bank were sampled initially in July, 2005 before the prescribed fire (defined as long-term seasonal sampling). More intensive sampling was initiated two days pre-fire, and continued three weeks post-fire. In general, the long-term seasonal samples (between September, 2005 and September 2007) were collected bimonthly when the plot was accessible due to a drought condition, whereas post-fire sampling events varied by parameter. Post-fire surface water sample collection started the day of the fire, pore water started two days after the fire, and the first periphyton samples were collected one month after the fire. For long-term surface water samplings, grab samples were collected at all six sampling stations. Autosamplers (Streamline 800SL, Hach Company, Loveland, CO) were deployed for pre- and post-fire sampling events at the upstream, one within burned plot and both downstream locations and programmed to collect samples hourly. While the pre-fire hourly samples were combined into one daily sample, the 1st day post-fire samples were composited into two samples, the first included samples from 0 to 9 hrs and the second 9 to 21 hrs to capture immediate change post-fire. Starting the 2nd day post-fire and for the remainder of the sampling period, the hourly samples were composited into one daily sample. In addition, grab samples were collected at all six sampling stations within one hour of the fire. All samples were analyzed for TP, total dissolved phosphorus (TDP), SRP, TC, dissolved inorganic carbon (DIC), total Kjeldahl nitrogen (TKN) and total dissolved Kjeldahl nitrogen (TDKN) following standard methods (APHA, 1998).

Soil pore-water wells consisting of about 6 cm PVC pipe with 10 cm of 1-mm screening at the bottom of the well were installed such that the screened section would be from 20 to 30 cm below the peat surface. Short-term samples were collected five days before the prescribed fire and on days two, nine and twenty post-fire. Sample analyses were the same as for surface water, excluding TC and DIC.

*In situ* surface water pH, DO, and temperature were recorded using YSI$^{TM}$ 600XLM sondes (YSI Corp., Yellow Springs, CO). The sondes were installed vertically such that the probes were in the middle of the water column; instantaneous measurements were recorded concurrently with surface water quality sample collection. The sondes were deployed and programmed to log data every 30 minutes starting eight days pre-fire until three weeks post-fire. For sampling before and during the fire, within the burned plot, the entire sonde was installed horizontally below the water surface to prevent fire damage; the sonde probe was approximately 3 cm below the surface of the water and 3 cm above the sediment layer.

Air, water, and soil temperatures were recorded using HOBO type K thermocouples (Onset Computer Corporation, Bourne, MA) installed 5 cm above the water surface, 5 cm below the water surface and 5 cm below the peat surface. The HOBO data loggers were deployed the day before the fire and programmed to collect readings every five seconds during the daylight hours of the fire. The data loggers were removed from the field about three hours after the fire.

Periphyton samples were collected one week pre-fire, one month post-fire, and three months post-fire from all plots and sampling stations using a procedure modified from McCormick et al. (1998). Samples were collected within a 0.25 m$^2$ quadrat frame that was divided into four equal quadrants. Macrophyte vegetation within one quarter of the quadrat was clipped at the soil surface and placed in gallon Ziplocs for later removal of epiphyton. All floating metaphyton within the quadrat including associated *Utricularia* spp. was collected and placed in a Ziploc bag. Then, three 3–10 cm deep cores were taken randomly in the quadrat using a syringe-corer and the core was extruded into a whirl pack. All samples were placed into the iced coolers and returned to the lab within 8 hrs and they were then dried at 80 °C for one week and analyzed for TP.

Seed bank soil samples were collected 12 days pre-fire and one day post-fire at all three within burned plot sampling stations. A total of nine soil cores were collected (three at each sampling station) using a 9.9 cm internal diameter corer to a depth of 10 cm (Miao & Zou 2009 for details). The cores were stored on ice in the field and kept in a cold room with the temperature around 4 °C until processing. All identifiable plant biomass, including live roots and rhizomes, was removed from each sample. The remaining volume of soil, a maximum of 500 mL ($cm^3$), was used in a seed bank germination assay. The soil samples were spread to a thickness of 1 cm in pots filled with washed sand. Saturated conditions were maintained in all pots for the duration of the experiment using a circulation pump. All newly emergent seedlings were identified and counted. Unidentified seedlings were removed from the original germination container and grown until they could be positively identified. Germination monitoring continued for six months until no additional seeds germinated.

### Data analysis

Volumetric ash nutrient content within the water column was calculated by multiplying the ash mass (g) by ash nutrient concentration (g/g), ash collector surface area (0.129 $m^2$) and water depth (m) and expressed as mg nutrient $L^{-1}$ of water.

The overall Fire Project was designed using a modified BACIPS that requires a relatively long period of before treatment data, thus, it is suitable for assessing long-term treatment effects. However, to capture the quick ecosystem responses to fire, sampling programs need to have frequent sampling events over a relatively short period of time. As a result, long-term before-fire and short-term after-fire sampling regimes are unbalanced, both in number and sampling interval, and thus cannot be easily analyzed within a BACI-Analysis of Variance or BACIPS t-test (e.g., Stewart-Oaten 1996, Hewitt et al. 2001, Miao et al. 2009). Regression analyses were conducted using the differences between data collected by pairing the upstream sampling station and the within burned plot, 25 m downstream or 100 m downstream sampling stations. Separate pre- and post-fire regressions were conducted for both surface and pore water nutrients. To detect whether these relationships changed as a consequence of fire, the slopes and intercepts of the regression analyses of data from the paired sites (between burned and control plots) were evaluated using analysis of covariance (ANCOVA). Significant differences in the slopes and/or intercepts suggest a fire effect, while similar slopes and intercepts between pre- and post-fire indicated no fire effects. Similar pre- and post-fire regression analyses were also conducted for SRP vs TP to test the hypothesis that concentrations of soluble nutrient forms increased post-fire. Moreover, peak percent changes, response time, duration, and downstream distance were calculated.

The number of germinated seedlings per $m^2$ was determined by the total number of germinated seedlings divided by the area of soil allowed to germinate in a 500 $cm^2$ pot. The difference between pre- and post-fire seed germination was evaluated using analysis of variance (ANOVA) on germination percentages to determine if the various species responded differently to fire. Three independent t-tests, one of each species evaluated (cattail, sawgrass and all other species) were conducted to determine whether the difference in pre- and post-fire seed germination was significantly different from zero.

## Results

### Ash return and ash nutrient concentrations

A maximum air temperature of 343 °C and an average temperature of 176 ± 91 °C were recorded and the temperature change lasted on average 6.5 ± 2 min. Not any change was found for both water and soil temperature.

The prescribed fire burned only cattail dead leaf litter throughout the plot. Live cattail leaves before the fire transitioned to standing dead, then fell within a few days post-fire. As a result, pre-fire dead leaves were the source of ash collected in all collectors. Approximately 10.7 ± 6.4 g $m^{-2}$ of ash was added to the burned plot. Adjusted by water depth at the time of the fire (11 cm), the concentration of ash added to the water column within the burned plot was, approximately 97.4 mg $L^{-1}$. Ash TP and $Ca^{2+}$ concentrations were approximately 10 and 22 times greater, respectively, than pre-fire leaf litter concentrations, while ash TN and TC were 86 % and 50 % of the leaf litter, respectively (Table 1). Ash pH ranged from 8.16 to 11.84.

**Table 1.** The chemical composition (mean ± SD) of ash collected during the fire. Sample size for all parameters was 11, except for $NO_3^-$ (n = 10) and pH (n = 9). Calculated concentrations were based on the addition of ash to the water column assuming that water depth across the entire plot was 11 cm as was measured at the within burned plot station.

| | g kg$^{-1}$ ± SD | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | TP | SRP | TN | $NH_4^+$ | $NO_3^-$ | TC | $Ca^{2+}$ | pH |
| Fire ash nutrient concentration | 3.45 ± 1.0 | 0.02 ± 0.02 | 5.95 ± 2.0 | 0.04 ± 0.02 | 0.04 ± 0.05 | 213 ± 45 | 204 ± 66.6 | 10.0 ± 1.3 |
| Pre-fire leaf litter nutrient concentration | 0.34 ± 0.17 | – | 6.03 ± 2.05 | – | – | 428 ± 50 | 9.27 ± 1.50 | – |
| Ash nutrient content added to water column (mg $L^{-1}$) | 0.34 | 0.002 | 0.58 | 0.004 | 0.004 | 20.74 | 19.9 | – |

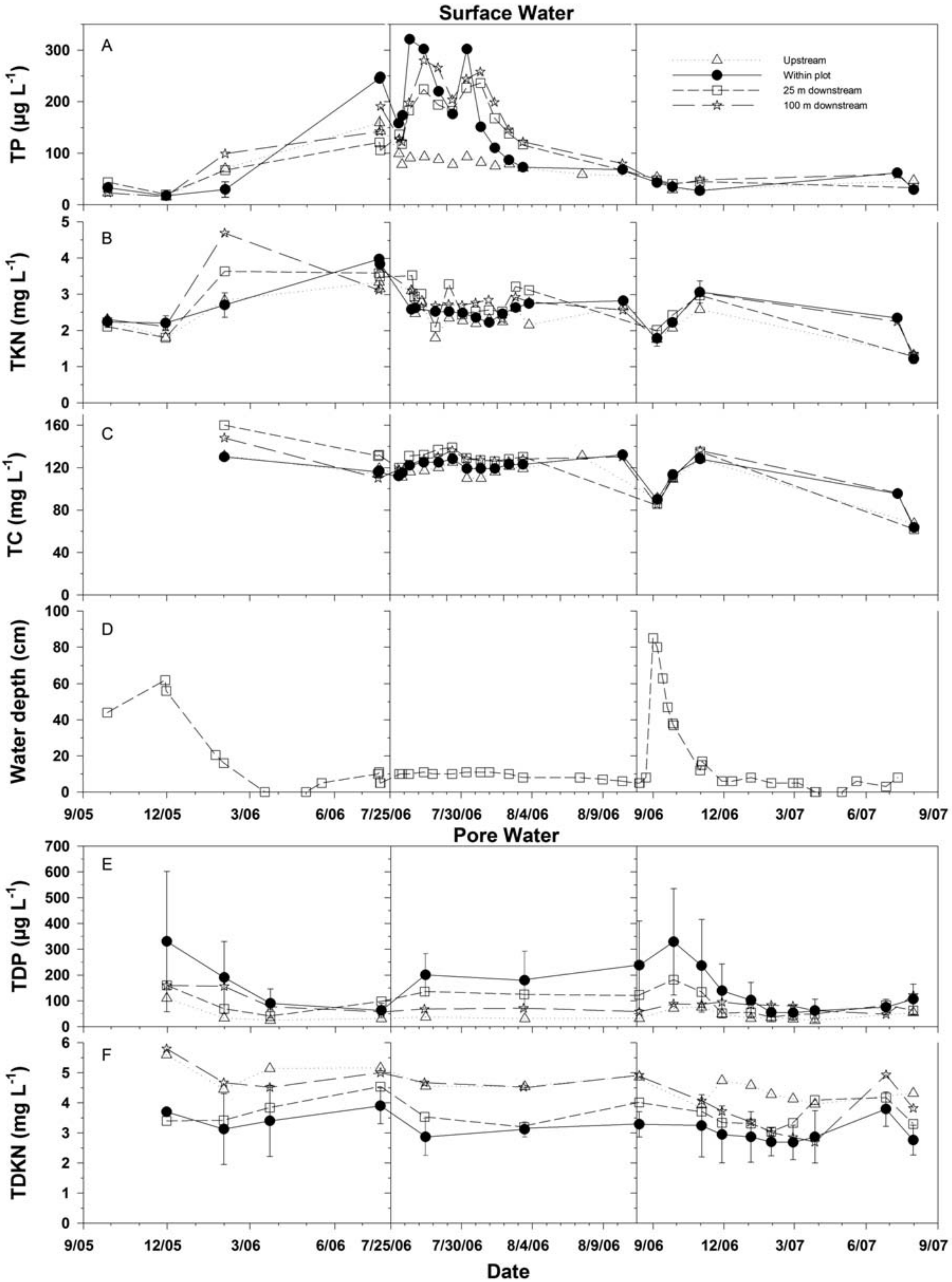


**Fig. 2.** Changes in surface and pore water nutrients and water depths pre-, the day, and post-day the prescribed fire. Surface water samples were collected by autosamplers at four locations (upstream, within the burned plot, 25 and 100 m downstream). Each sample was composited at different frequencies (see Methods for details). Pore water samples were collected at the same locations (upstream, within the burned plot, 25 and 100 m downstream) except for three replicates for the within burned plot. Surface water depths were collected from a staff gage installed at the 25 m downstream sampling station (n = 14). TP = total phosphorus, TKN = total Kjeldahl nitrogen, TC = total carbon, TDP = total dissolved phosphorus and TDKN = total dissolved Kjeldahl nitrogen. Note that the scale of the x-axis in the middle panel is by day, while that of other two panels is by month.

### Surface and pore water nutrient dynamics

No pulse of surface water TP was observed upstream of the plot during the 10 days immediately after the fire, but increases were observed at the within burned plot and two downstream stations (Fig. 2). Average TP concentrations over that time period were 82 ± 11, 187 ± 92, 180 ± 42, 193 ± 67 μg $L^{-1}$ for the upstream, within burned plot, 25 m downstream, and 100 m downstream, respectively. Two peak TP pulses, 321 μg $L^{-1}$ and 302 μg $L^{-1}$, occurred at the within burned plot sampling station on days one and five, respectively and were about 253 % and 225 % greater than the upstream control (Table 2). Within nine days of the fire, surface water TP concentrations within the burned plot decreased to levels similar to the upstream control.

For the two downstream stations, the two TP peaks occurred on days two and six, one day later than the peaks observed at within burned plot (Fig. 2A). In addition, the TP pulses declined more slowly (by three to four days) at the downstream locations. Surface water SRP showed similar dynamics to that of TP.

Neither surface water TKN (2.6 ± 0.3 mg $L^{-1}$, average post-fire concentration of all sampling stations) nor TC (123.7 ± 7.1 mg $L^{-1}$, average post-fire concentration of all sampling stations) showed any post-fire pulse at any of the sampling stations (Fig. 2C and 2E).

Although measured less frequently, pore water TDP concentrations showed a similar, but dampened, post-fire P pulse compared to that of surface water (Fig. 1E and Table 2). Increased pore water TDP post-fire starting on day two lasted longer than three weeks. The second increase (September 27, 2006 sampling event) in TDP was detected about two months post-fire for all four sampling stations. It is important to note that no pore water samples were collected on day one post-fire, so the peak may have occurred sooner. There was no clear pattern for post-fire pore water TDKN concentrations, as both upstream and 100 m downstream were consistently greater than within burned plot and 25 m downstream (Fig. 2F).

The differences between the upstream and both the within burned plot and downstream stations were further assessed using regression analyses (Fig. 3). For surface water TP, significant positive relationships were found for both pre- and post-fire samplings regardless of sampling stations (Fig. 3A, Table 3). However, the regression analyses of surface water TP between pre- and post-fire exhibited different intercepts and or slopes, i.e., post-fire regression analyses showed significantly greater intercepts than pre-fire. In particular, the slope from the post-fire regression analysis between the upstream control and the within burned plot was greater than that of pre-fire. Overall, the regression analyses indicates that the increases of post-fire surface water TP within the burned plot and the two downstream stations were independent from the upstream control and that the within burned plot exhibited the greatest increases as shown in Figure 3A with the closed circles having the highest concentrations.

For surface water TKN, one significant regression analysis result was found between the upstream and within burned plot with a lower intercept and slope for

**Table 2.** The responses of surface and pore water quality following a prescribed fire within the burned plot. Response time is defined as the time between the fire and the first noticeable impact from the fire reported in days, except for pH which is reported in minutes. Peak concentration is the peak concentration over the extent of the study period, while duration is amount of time that the within burned plot station differs from the upstream station. The upstream and downstream data used in the calculation were collected the same day. Percent change in pH, DO and temperature is based on daily peaks for both within the burned plot and upstream.

| Process or parameter | Response time | Peak concentration | % change from upstream | Duration (Weeks) | Downstream response (m) |
|---|---|---|---|---|---|
| Surface water | | | | | |
| Total phosphorus (μg $L^{-1}$) | 1 day | 321 | 253 | <2 | >100 |
| Total dissolved phosphorus (μg $L^{-1}$) | 1 day | 251 | 173 | <2 | >100 |
| Soluble reactive phosphorus (μg $L^{-1}$) | 1 day | 231 | 645 | <2 | >100 |
| pH | 30 minutes | 8.37 | 18 | >3 | 0 |
| Dissolved oxygen (mg $L^{-1}$) | <13 days | 6.9 | 298 | >3 | 0 |
| Temperature (°C) | 1 day | 34.46 | 18 | >3 | 0 |
| Pore water | | | | | |
| Total phosphorus (μg $L^{-1}$) | <2 days | 246 | 515 | >3 | >100 |
| Total dissolved phosphorus (μg $L^{-1}$) | <2 days | 238 | 644 | >3 | >100 |
| Soluble reactive phosphorus (μg $L^{-1}$) | <2 days | 222 | 754 | >3 | >100 |

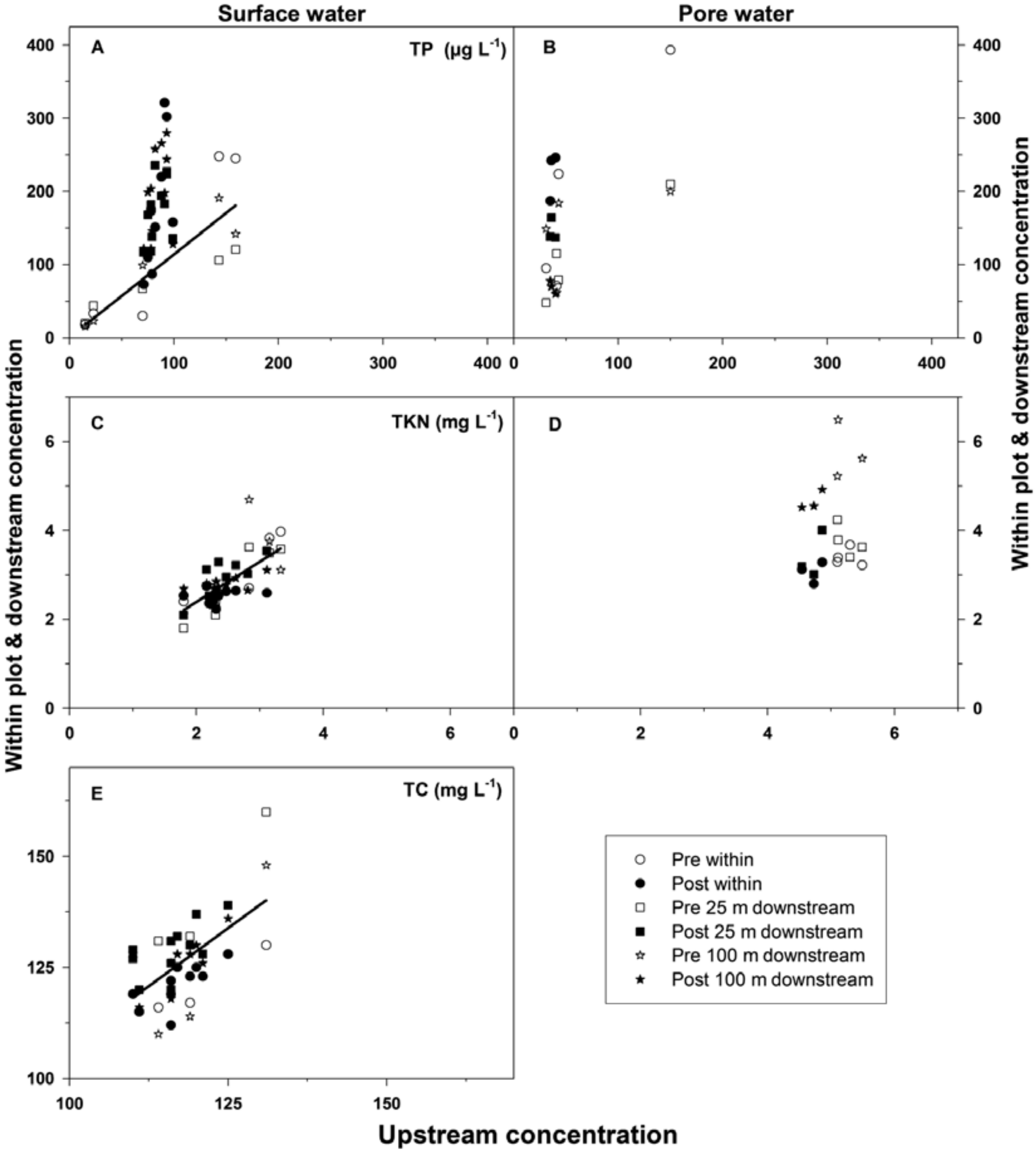


**Fig. 3.** Surface and pore water regression analyses using the upstream station concentrations as an independent variable (x) and within the burned plot and both downstream station concentrations as dependent variables (y). Sample size (n) for pre-fire surface water nutrients was 15 except for total carbon (n = 13) and post-fire the sample size was 33. Regression lines were given when regression was significant at $P \leq 0.05$. For pore water nutrients, sample sizes were 24 and 18 for pre- and post-fire, respectively. TP = total phosphorus, TKN = total Kjeldahl nitrogen and TC = total carbon.

**Table 3.** P-values of ANCOVA results for the regressions in Fig. 3 using the upstream station as a control (independent variable) and the within burned plot or downstream stations as dependent variable for both pre- and post-fire and surface water (SW) and pore water (PW) nutrients. "ns" means not significant at $P < 0.05$.

| | TP | | | TKN | | | TC | | |
|---|---|---|---|---|---|---|---|---|---|
| | coincidence | intercept | slope | coincidence | intercept | slope | coincidence | intercept | slope |
| SW upstream-within | < 0.01 | < 0.01 | 0.02 | 0.01 | ns | 0.01 | < 0.01 | < 0.01 | ns |
| SW upstream-25 m downstream | 0.04 | 0.02 | ns | ns | ns | ns | 0.06 | ns | 0.03 |
| SW upstream-100 m downstream | 0.02 | 0.01 | ns | ns | ns | ns | < 0.01 | < 0.01 | 0.01 |
| PW upstream-within | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| PW upstream-25 m downstream | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| PW upstream-100 m downstream | ns | ns | ns | ns | ns | ns | ns | ns | ns |

post-fire measurements (Fig. 3C, Table 3). For surface water TC, regressions between all paired sampling stations showed significant differences in either intercepts or slopes or both (Fig. 3E and Table 3). No relationship was found between upstream and within burned plot or downstream stations for pore water nutrients (Figs. 3B and 3D, and Table 3).

Figure 4 highlights the relationships between soluble P (including SRP and TDP) and TP in surface and pore water pre-and post-fire. Overall, significant and positive relationships were found for P in both surface and pore water regardless of fire (Figs. 4A to 4D, coincident in Table 4). The pre- and post-fire regressions of P were significantly different in intercepts and slopes (Table 4). Significantly greater slopes and intercepts suggest a higher concentration of soluble P post-fire. Moreover, immediately before the fire, 61 % and 28 % of surface water TP was comprised of TDP and SRP, respectively. However, during the peak surface water TP concentrations following the fire, as much as 78 % and 72 % of the TP was comprised of TDP and SRP, respectively.

The relationships between TDKN and TKN for surface and pore water differed (Fig. 4E and 4F, and Table 4). There was no difference between pre- and post-fire in surface water, but a difference existed in pore water. The DIC and TC relationships pre- and post-fire were examined only for surface water (Fig. 4G and Table 4) and were similar to those of nitrogen.

**Table 4.** Regression statistics of different forms of phosphorus, nitrogen, and carbon in surface water (SW) and pore water (PW) between pre-and post-fire. Pre-fire data is reported for all six sampling stations for both surface and pore water. Post-fire surface water data is for the upstream station, one within burned plot station, and the 25 m and 100 m downstream stations. "ns" refers not significant at $P < 0.05$.

| | Coincident | Intercept | Slope |
|---|---|---|---|
| SW SRP vs TP | < 0.0001 | 0.06 | < 0.0001 |
| PW SRP vs TP | 0.0074 | 0.0094 | ns |
| SW TDP vs TP | < 0.0001 | < 0.0001 | ns |
| PW TDP vs TP | 0.0006 | 0.0318 | 0.0043 |
| SW TDKN vs TKN | 0.0031 | 0.0468 | 0.0166 |
| PW TDKN vs TKN | <0.0001 | <0.0001 | 0.0495 |
| SW DIC vs TC | 0.0005 | 0.0083 | 0.02 |

## Water chemistry and temperature in the burned plot

The average surface water pH, DO, and temperature were 7.3 ± 0.2, 2.3 ± 0.8 mg $L^{-1}$, and 20.9 ± 3.7 °C, respectively. The pH at the burn plot peaked at 8.4 within 15 min after the fire, while no pH change was observed at the upstream or either downstream stations (Fig. 5A). The pH increased throughout the duration of the monitoring and the average pH was 7.4 ± 0.1 for the within burned plot station and 7.1 ± 0.1 for the upstream station during the third week post-fire.

A significant increase in daily peak DO was detected by the third week post-fire when peak concentrations within the burned plot were as much as 400 % greater than the upstream peaks (Fig. 5B). An increase in the daily maximum water temperature was apparent starting the day of the fire (Fig. 5C). The increase in surface water temperature within burned plot was roughly 2 °C the day of the fire and 5 °C by the second day. The daily average water temperature of the within burned plot was 2.3 °C greater than the upstream and two downstream stations on day 19, post-fire.

## Periphyton and seed bank germination

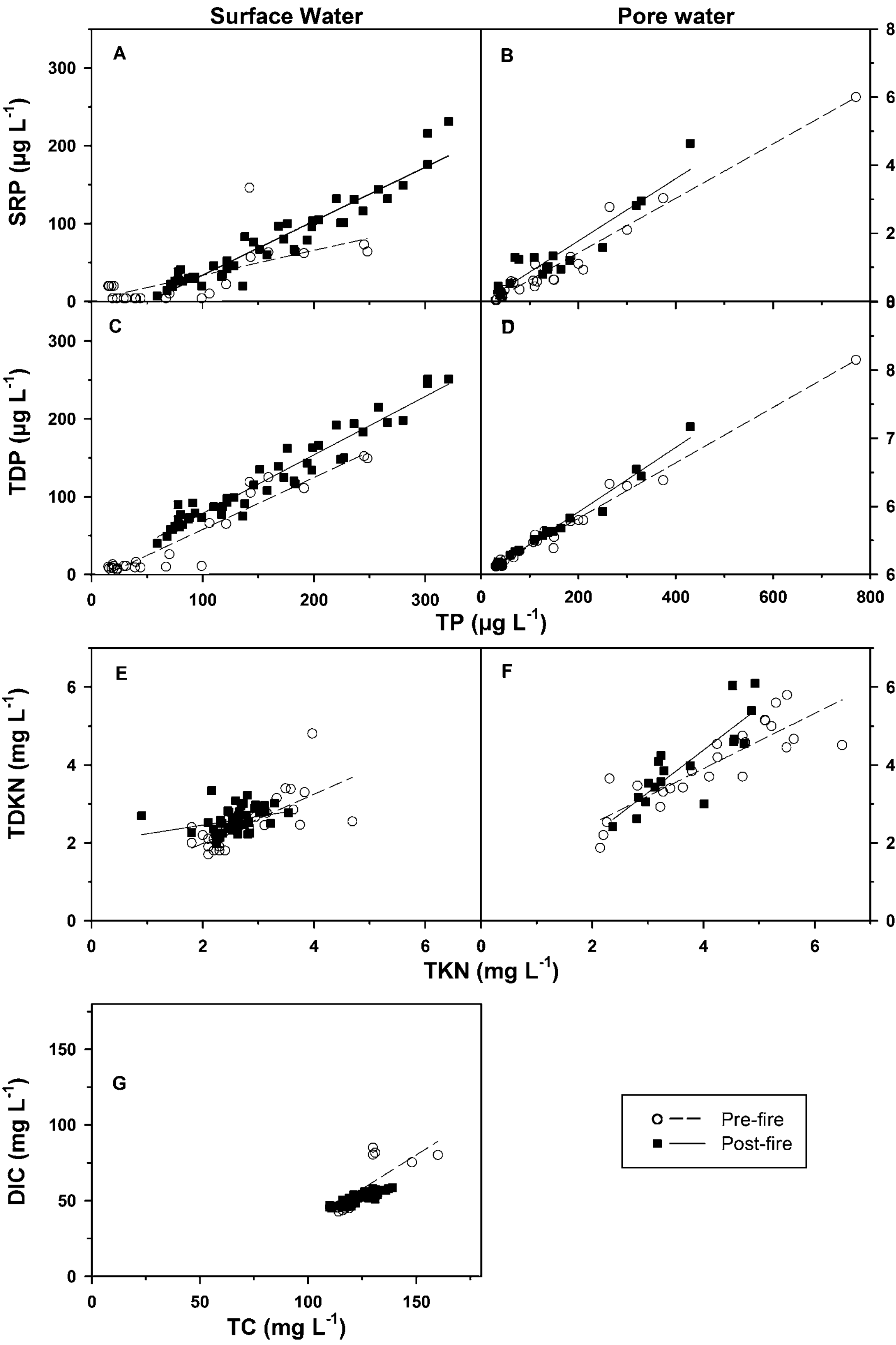
Samples taken one day pre-fire showed no visible periphyton biomass at any of the sampling locations within burned plot or 25 m downstream. Epiphyton (periphyton grown on the surface of submerged plants) was the dominant periphyton present during the first month following the fire and thereafter. No periphyton growing on the soil surface (epipelon) was noted either pre- or post-fire at any of the sampling stations. As for periphyton nutrient concentration, one month post-fire, average periphyton TP concentrations from samples collected from within burned plot were

**Table 5.** Seed germination totals for samples collected within the burned plot **about two weeks** pre-fire and **one** day post-fire, n = 9 for both sampling periods.

| | Cattail | Sawgrass ($\#m^{-2}$) | Other species |
|---|---|---|---|
| Pre-fire | 4444 ± 1872 | 42 ± 38 | 980 ± 1118 |
| Post-fire | 2629 ± 1130 | 83 ± 61 | 1094 ± 929 |

►

**Fig. 4.** Regression analyses of nutrient concentrations for surface and pore water. Surface water samples were collected from four sampling stations (upstream, within burned plot, 25 m and 100 m downstream). The within burned plot pore water concentrations are an average of three sampling stations. The sample size (n) was 12 for upstream, within burned plot and 100 m downstream and n = 11 for 25 m downstream for surface water. For pore water n = 3 for all sampling stations. SRP = soluble reactive phosphorus, TDP = total dissolve phosphorus, TP = total phosphorus, TDKN = total dissolved Kjeldahl nitrogen, TKN = total Kjeldahl nitrogen, DIC = dissolved inorganic carbon and TC = total carbon.


Surface Water
Pore water
A
B
C
D
E
F
G
SRP (µg L-1)
TDP (µg L-1)
TP (µg L-1)
TDKN (mg L-1)
TKN (mg L-1)
DIC (mg L-1)
TC (mg L-1)
0
100
200
300
800
600
400
200
0
8
7
6
6
4
2
150
50
Pre-fire
Post-fire

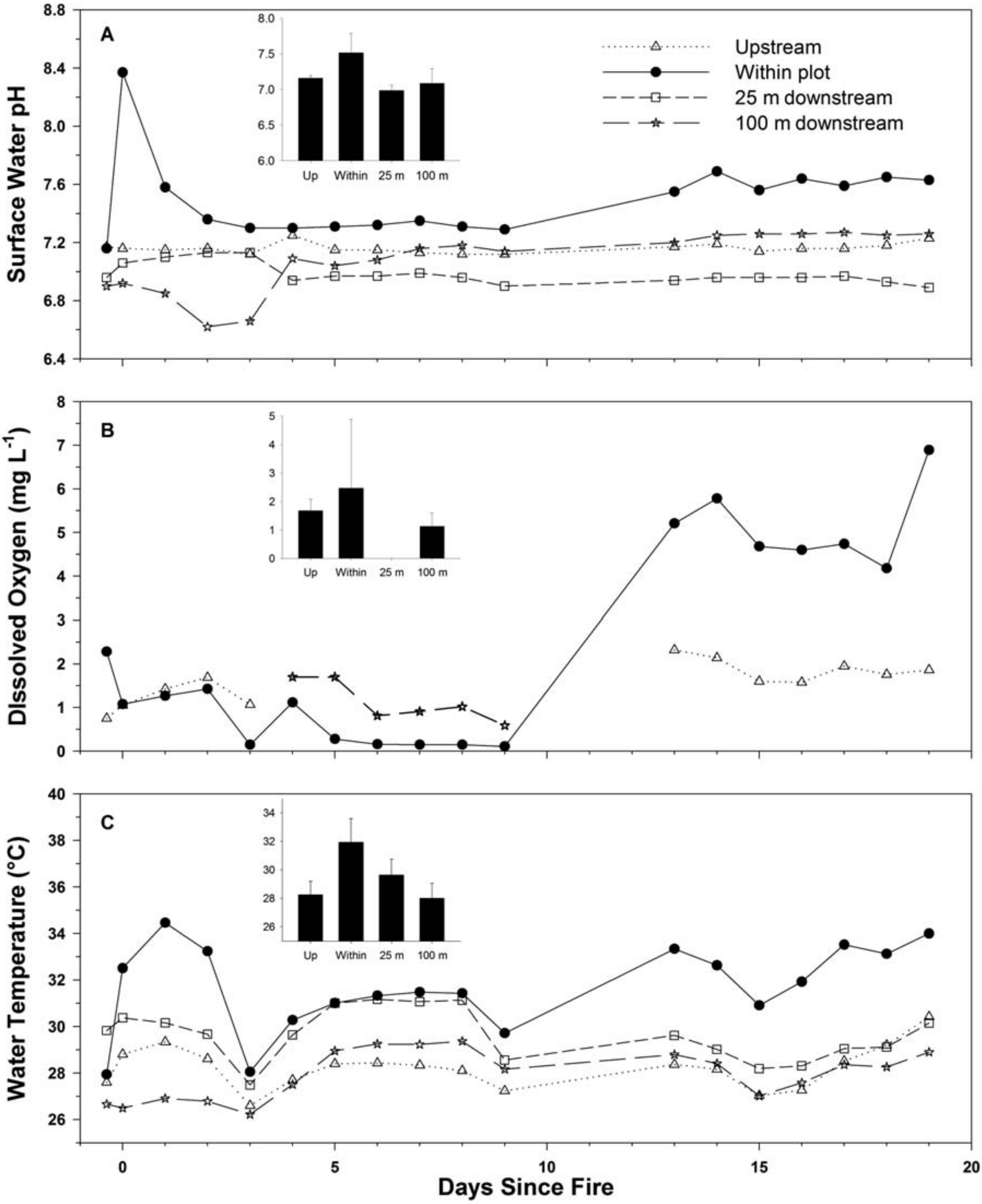


**Fig. 5.** Peak daily *in situ* **(a)** surface water pH, **(b)** dissolved oxygen and **(c)** water temperature measured at the upstream, within burned plot and 25 and 100 m downstream stations. The sample size (n) was 18 for all four sampling stations for pH and temperature. The sample size for DO was 18 for the within burned plot, 12 for upstream, 0 for 25 m downstream and 6 for 100 m downstream. The insert column-graph in each graph shows the means ± standard deviation of the four locations during the first nineteen days post-fire. The insert graphs have the same y-axis labels as their counterpart graph.

3,495 ± 320 mg $kg^{-1}$ and decreased to 1,730 ± 219 mg $kg^{-1}$ two months post-fire.

Seed bank germination exhibited differences between pre- and post-fire collections, but these differences varied with species. There was a significant (ANOVA, $P < 0.05$) decrease (41 %) in total number of cattail seed germinated between pre- and post-fire samples. On the other hand, while not statistically

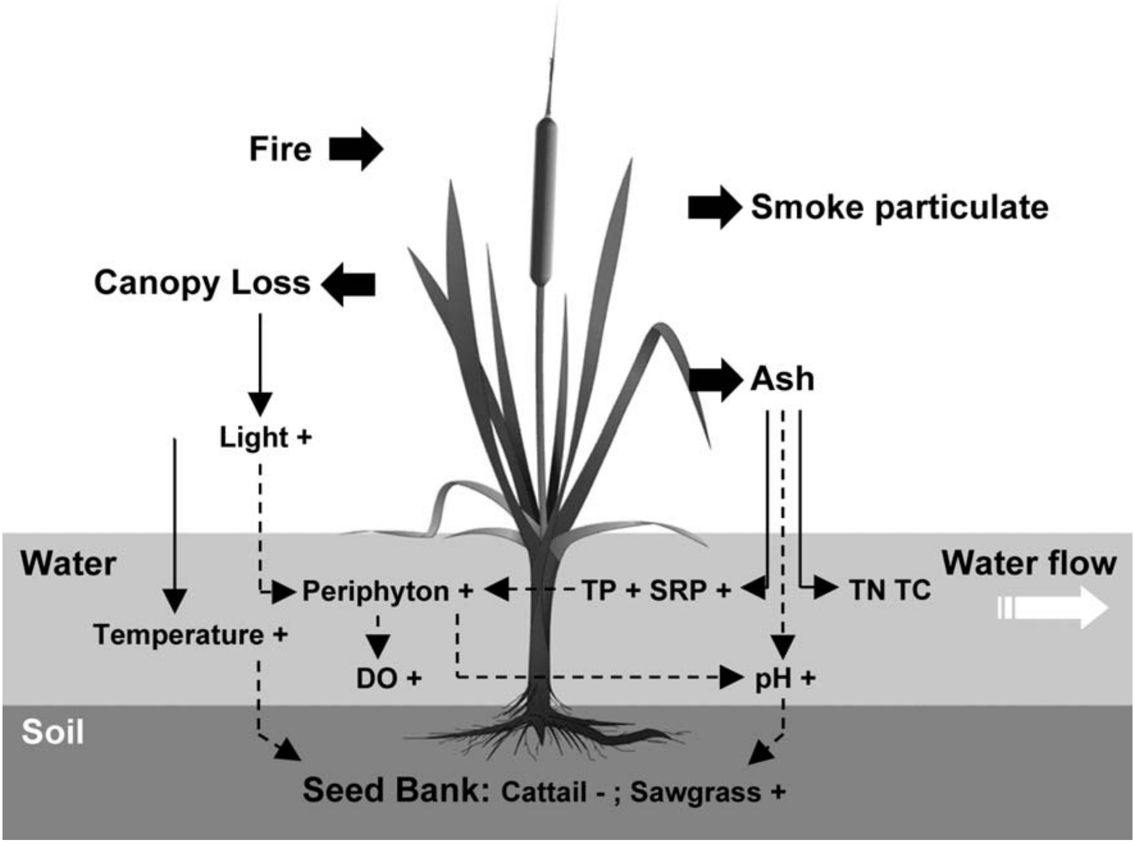


**Fig. 6.** A conceptual model highlighting quick ecosystem responses assessed by the present study to a prescribed fire in a cattail dominated wetland.

significant, seed germination of sawgrass and other species (mainly *Amaranthus* spp. and *Sagittaria* spp.) showed an increase (97 % and 12 %, respectively) following the fire.

## Discussion

The most striking feature demonstrated quantitatively by this study was the varying degrees of the speed, magnitude, duration, and dispersion of ecosystem responses to the prescribed fire. While some parameters responded in minutes (pH) or hours (water temperature and quality and seed bank), others responded in days and weeks (periphyton and DO). Some of the responses were brief (surface water TP), others were lengthy (water temperature) depending on which parameter was examined. Significant increase in surface water TP was detected 100 m downstream of the fire, and might have extended further. The only observable post-fire pulse in water nutrients occurred in the form of dissolved inorganic P.

The linkages among ecosystem processes examined in this study are summarized in Fig. 6. The prescribed fire removed plant canopy and released nutrients back into the system. A series of immediate ecosystem responses were revealed, including : (1) immediate pulses in surface water pH and P, both TP concentration and its soluble forms; (2) elevated downstream P transport to at least 100 m; (3) increased DO and temperature in the surface water; (4) increased periphyton TP concentrations; and (5) altered seed bank germination. While surface water chemistry recovered rapidly (within 10 days), pore water P concentrations were elevated for three weeks, and other observed ecosystem responses (surface water pH and DO, periphyton P concentration and water temperature) lasted for months following the fire. Periphyton growth was minimal during the first week after the fire, the brief duration of this pulse was probably due to a combination of downstream transport (which we estimated at approximately 2 m per hour), and the adsorption of SRP by and settling of particulate P to the floc layer. Periphyton biomass increased approximately two weeks after the fire and was probably directly related to increased light reaching the water column. Overall, immediate ecosystem responses to the prescribed fire occurred at multiple temporal and spatial scales. Whether these short-term responses have sustained effects and how they shape other ecosystem entities and processes is currently being investigated and will be assessed by our long-term studies to provide vital understanding of wetland ecosystem recovery post-fire.

The immediate pH pulse in surface-water, presumably attributable to the addition of basic ions, plays a role in the dynamics of P forms and P availability in the water column and superficial sediments, as well as DIC dynamics at a short-time scale (Gu et al. 2008). Increased pH increases the potential for $CaCO_3$ precipitation with SRP and decreases P availability. Because dissolved $CO_2$ concentration decreases as pH increases (Wetzel 2001), partial pressure of $CO_2$ in the surface waters and the flux of $CO_2$ to the atmosphere from aquatic systems should decrease correspondingly (Maberly 1996), which was also observed during our study (Gu et al. 2008 for details).

The instant increase in water temperature of 2–3 °C following fire was largely related to the removal of plant litter and canopy. Increases in soil temperature were also found within the burned plot. Increases in water and soil temperature could have profound impacts on microbial decomposition and nutrient cycling as well as the solubility of gases (e.g., $CO_2$ and $O_2$). Greater light availability, along with higher soil and water temperature and nutrient concentration may result in increased periphyton growth should the open canopy be persistent. These responses may create conditions that favor reestablishing periphyton communities.

Fire impacts on seed germination and seed bank dynamics can be positive via smoke (Roche et al. 1998, Flematti et al. 2004) or negative by heat (e.g. Flematti et al. 2004). Literature reporting the effects of fire on seed bank germination primarily focused on terrestrial systems such as forests, grasslands, and agricultural fields (Adkins et al. 2003, and references therein). Different impacts of fire on seed bank germination between cattail and sawgrass were detected in this study and elsewhere (Miao & Zou 2009), which might relate to their seed size, structure, and morphology. Regardless of the factor(s) governing the change in germination, immediate responses of seed bank germination were detected for both cattail and sawgrass. Detailed studies on this critical vegetation re-establishment will be explored more closely during future fire events of the project.

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