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Fire Characteristics and Hydrologic Connectivity Influence Short-Term Responses of North Temperate Lakes to Wildfire

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Key Points:

- We observed post-wildfire increases in nutrients, dissolved organic carbon, sediments, and acidity and reduced water clarity in lakes
- Water quality responses were often persistent or cumulative throughout the summer, especially for lakes with tributaries from burned areas
- High-severity and shoreline burns resulted in a nearly two-fold increase in total phosphorus concentration compared to control lakes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Despite increasing wildfires, few studies have investigated seasonal water quality responses to wildfire characteristics (e.g., burn severity) across a large number of lakes. We monitored 30 total lakes (15 burned, 15 control) monthly following the Greenwood Fire in Minnesota, USA, a lake-rich region with historically prevalent wildfire. We found increases in median concentrations of total nitrogen (68%), total phosphorus (70%), dissolved organic carbon (127%), total suspended solids (71%), and reduced water clarity (48%) and pH (0.45) in burned lakes. Post-wildfire responses in drainage lakes were often persistent or cumulative throughout the open-water season, compared to isolated lakes. Total phosphorus (TP) increased linearly with watershed high-severity burns, and shoreline high-severity burns explained more variation in TP than lake morphometry and watershed variables. Post-wildfire chlorophyll-a responses were nonsignificant and inconsistent, possibly due to light limitation. Our results suggest that increasing wildfires have significant potential to affect water quality of inland lakes.

Plain Language Summary Despite increasing wildfire activity, there has been limited research on wildfire effects on lakes. We monitored lake water quality throughout summer 2022 following the 2021 Greenwood Fire in Minnesota, USA, a lake-rich region where wildfire was historically common. We found that lakes with burned watersheds were more nutrient- and carbon-rich and more acidic and murky. Responses often increased throughout the summer, particularly for lakes with tributaries from burned areas. However, murkier water may have prevented increased nutrients from increasing algae abundance. Water quality responses were greater following burns near lake shorelines and of greater severity, reflecting damage to vegetation and soil. Our results suggest that increasing wildfire under climate change may degrade lake water quality.

1. Introduction

As wildfire activity continues to increase, concern is growing over the consequences for water quality. Past research has primarily focused on streams and rivers, particularly in the western US (reviewed by Gresswell, 1999; Bisson et al., 2003; Bixby et al., 2015; Paul et al., 2022). In contrast, there are fewer studies on lakes and most were conducted in boreal or subarctic regions, particularly Canada (reviewed by McCullough et al., 2019; Robinne et al., 2020). Although these past studies often anticipated increased post-wildfire concentrations of dissolved organic carbon (DOC), nutrients, and algal biomass, results for each of these variables have been somewhat inconsistent. For example, three Alberta-based studies found increased DOC from burned area runoff up to 2 years post-wildfire (Allen et al., 2003; McEachern et al., 2000; Scrimgeour et al., 2001), whereas studies from Québec, Alberta, and Northern Ireland found decreased DOC two to four years post-wildfire attributed to organic matter consumption in watersheds or regional factors such as hydrology and geology (Carignan et al., 2000; Evans et al., 2017; Olefeldt et al., 2013). Lack of observed increases in post-wildfire nutrient concentrations (nitrogen and phosphorus) have been attributed to rapid vegetation regrowth, soil properties, or interactions between lake metabolism and water residence time (Wright, 1976; McColl & Grigal, 1977; Marchand et al., 2009). Finally, lakes with observed post-wildfire nutrient increases have sometimes not experienced corresponding increases in

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algal biomass due to light limitation (related to post-wildfire DOC) or large pre-wildfire nutrient pools (Allen et al., 2003; Lewis et al., 2014; McEachern et al., 2000).

Numerous factors may explain inconsistences among past studies, including sample timing, flushing rates, and wildfire extent (Raoelison et al., 2022). Another possible explanation is that past studies typically monitored 1–10 lakes just once during the open-water season (reviewed by McCullough et al., 2019). Consequently, past studies may have suffered from low sample sizes or the inability to account for post-wildfire seasonal dynamics in water quality. Additionally, most past studies simply compared burned watershed versus control lakes and therefore essentially treated all wildfire disturbances equally (e.g., 1% and 100% watershed burned were treated the same in statistical analyses) (McCullough et al., 2019). This approach fails to account for the possibility that minor disturbances cannot override other water quality controls (e.g., lake morphometry, watershed variables) or that certain lake types may be more sensitive to wildfire. Specifically, drainage lakes may experience greater, faster responses to wildfire compared to isolated lakes because hydrologic connectivity influences delivery of nutrients and materials (Gergel et al., 1999). Therefore, disentangling effects of wildfire from those of other variables could identify what lake types and water quality variables are most sensitive to wildfire.

We might expect greater wildfire disturbance to produce greater water quality responses, but "wildfire disturbance" can be vague. Past studies have reported that percentage watershed burned was correlated with water quality responses, but examined only 5–10 lakes with mostly high percentage watershed burned and no lake studies have explicitly quantified effects of burn severity, an indicator of post-fire damage to vegetation or soil (McCullough et al., 2019). High-severity burns translate to greater water quality impacts in streams (Rhoades et al., 2011), so we might expect the same for lakes. Furthermore, numerous studies have linked riparian burns to stream water quality (Pettit & Naiman, 2007), but no studies have examined lake responses along shoreline burn gradients. Precise information on burn extent or severity may have been unavailable previously, but incorporating wide wildfire disturbance gradients (watershed and shoreline burn extent and severity) adds nuance to how wildfires actually disturb lake ecosystems.

Following a large northern Minnesota wildfire, we sampled more lakes than previous studies throughout the open-water season and along wide gradients of watershed and shoreline burn extent and severity. Notably, we conducted our research in an understudied, lake-dense region where wildfires were historically important but have been relatively infrequent since the early 20th Century. Prior to widespread fire suppression and Native American depopulation, wildfire occurred somewhere on the landscape approximately every 2 years and major regional wildfire years occurred approximately every 25 years, often coinciding with regional drought (Heinselman, 1973; Kipfmueller et al., 2017). Thus, wildfires may represent an increasingly common future disturbance due to climate change and long-term fuel accumulation. Specifically, we asked (a) How do lake water quality responses to wildfire vary throughout the open-water season and in relation to hydrologic connectivity and wildfire disturbance gradients? and (b) How do wildfire effects on lake water quality compare to effects of lake morphometry and watershed characteristics?

2. Methods

2.1. Study Area and Water Quality Sampling

The Greenwood Fire burned 108.44 km^2 of Superior National Forest, Minnesota, USA from August 15 through September 2021 (Incident Information System, 2021). This heavily forested landscape in the boreal transition zone contains abundant lakes, wetlands, and streams with negligible agriculture. The lightning-induced ignition coincided with unusually warm, dry weather (Figures S1 and S2 in Supporting Information S1), resulting in the ninth largest known wildfire in Minnesota since 1984 (MTBS, 2022).

Due to the unpredictably of wildfires, most previous studies have lacked pre-fire water quality data and instead compared burned and control groups (McCullough et al., 2019). In our case, this approach was necessary to monitor numerous lakes across key ecological gradients, in addition to only sporadic existing data for our study lakes (Soranno et al., 2019). We monitored 15 burned watershed lakes ("burned lakes") and 15 control lakes (0% watershed burned) (Figure 1a, Table S1 in Supporting Information S1) monthly from May to September 2022. For both burned and control lakes, we sought a regionally representative set of drainage and isolated lakes (Cheruvelil et al., 2021). We identified burned lakes that spanned wide gradients of watershed and shoreline burn extent and severity (Figure 1b, Figure S3 in Supporting Information S1) and control lakes within 10 km of

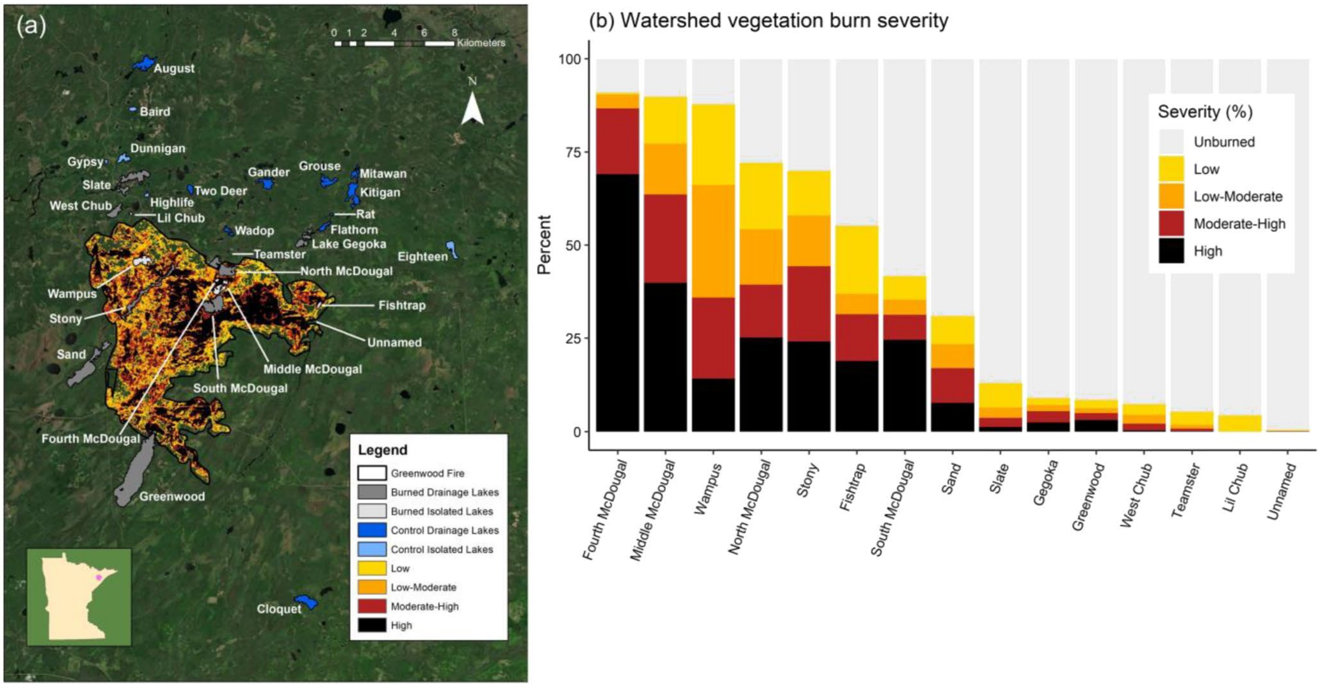

Figure 1. (a) Burned and control lakes in Superior National Forest, Minnesota, USA by hydrologic connectivity class and relative to the Greenwood Fire. (b) Watershed vegetation burn severity.

the burn area. The slight imbalance between burned (9 drainage, 6 isolated) and control (10 drainage, 5 isolated) sets (Table S1 in Supporting Information S1) was due to accessibility, but we analyzed drainage versus isolated lakes separately or as all lakes combined. We monitored total phosphorus (TP), total nitrogen (TN), DOC, pH, total suspended solids (TSS), chlorophyll-a (measure of algal biomass), water clarity (Secchi depth), and water temperature (all surface samples). See Supporting Information S1 for additional details on the study landscape, sampling, and processing methods.

2.2. Wildfire Disturbance Variables

We used a pre-classified soil burn severity raster (Figure S4 in Supporting Information S1) and a differenced normalized burn ratio (dNBR) raster (USGS, 2022) to calculate percentages of vegetation burn severity classes (Key & Benson, 2006) for lake watersheds and shorelines (represented by 100 m lake buffers) in ArcGIS Pro v 3.0 using lake and watershed polygons from LAGOS-US-LOCUS v 1.0 (Smith et al., 2021) (Figure 1b, Figures S4–S6 in Supporting Information S1). Due to correlations among wildfire variables, we focused on 6 variables representing watershed ("WS") and shoreline ("Shore") burn extent and severity (vegetation and soil), with an emphasis on high-severity ("HS") variables (Table S2 in Supporting Information S1).

2.3. Water Quality and Fire Data Analysis

We analyzed water quality distributions between burned and control lakes pooled across months and in individual months for drainage versus isolated lakes. We then used Kolmogorov-Smirnov (K-S) tests to compare these distributions, except for drainage versus isolated lakes due to sample size. We applied generalized additive models (GAMs) for each of our 8 water quality response variables (5-month averages; all natural log-transformed, except pH) to identify the top fire predictor (by adjusted R^2) (48 total candidate models) using the mgcv R package (Wood, 2011). Although we considered multivariate or threshold approaches, we opted for univariate GAMs owing to our sample size (15 burned lakes) and the often nonlinear relationships between wildfire and lake water quality. We then used variance partitioning analysis to assess the relative effects of our 6 wildfire disturbance variables versus those of lake morphometry and watershed variables on our 8 main water quality variables using the Hmsc R package (Tikhonov et al., 2022). Lake and watershed variables were chosen based on recent, large-scale assessments of water quality drivers (Read et al., 2015; Soranno et al., 2015). We obtained lake area, watershed area, drainage ratio (watershed area/lake area), and hydrologic connectivity class from LAGOS-US-LOCUS v 1.0 (Smith et al., 2021) and lake maximum depth from the mean of maximum depths recorded across all sampling events. Analyses included a random lake effect and a month effect to account for multiple sample events. K-S tests confirmed no significant differences in lake and watershed variables between burned and control lakes ($p > 0.05$).

3. Results

3.1. Post-Wildfire Water Quality: Temporal Patterns and Influence of Hydrologic Connectivity

We observed overall strong water quality responses of lakes to the Greenwood Fire, particularly for drainage lakes (Figures 2 and 3, Table S3 in Supporting Information S1). Burned lakes experienced greater median concentrations compared to control lakes (first and second numbers, respectively, followed by percentage difference) for TP (25.5 vs. 15.0 ppb; 70%), TN (873 vs. 521 ppb; 68%), DOC (21.1 vs. 9.3 ppm; 127%), and TSS (3.6 vs. 2.1 mg/L; 71%) and reduced water clarity (0.9 vs. 1.73 m; 48%) and pH (7.0 vs. 7.45) across all months (K-S $p < 0.05$; Table S4 in Supporting Information S1), with consistently greater median differences for drainage lakes versus isolated lakes (TP: 80% vs. 53%; TN: 80% vs. 57%; DOC: 119% vs. 91%; TSS: 80% vs. 50%; pH: 0.48 vs. 0.08, respectively). An exception was water clarity, for which median decreases for burned drainage and isolated groups were similar (53% and 54%, respectively).

Throughout the open-water season, TP was relatively stable in burned drainage and control lakes, but decreased in burned isolated lakes (Table S3 in Supporting Information S1, Figure 3a). In contrast, TN steadily increased over time in both burned drainage and burned isolated lakes, but more so in drainage lakes (Figure 3b). DOC steadily increased and water clarity steadily decreased in burned drainage lakes throughout the season, but both were relatively stable in burned isolated lakes and control lakes (Figures 3c and 3g). Differences between burned and control drainage lakes for TP, TN, DOC, and water clarity all consistently increased from May to September, whereas differences were more stable for isolated lakes. Conversely, differences in TSS between burned and control drainage lakes were greatest in May (2.9 mg/L; 145%), whereas corresponding differences for isolated lakes were greatest in July (2.7 mg/L; 135%) (Table S3 in Supporting Information S1, Figure 3e). Burned drainage lakes were consistently more acidic in all months except September (pH = 7.58), marginally exceeding control drainage lakes (pH = 7.49), but differences were otherwise relatively stable between burned and control isolated lakes. Overall, these results suggest that first-year wildfire effects on water quality can be persistent or cumulative throughout the open-water season, particularly for drainage lakes.

Algal biomass (chlorophyll-a) and surface water temperatures were not significantly different between burned and control lakes across all months (Tables S3 and S4 in Supporting Information S1, Figures 2f and 2h). Differences were also not significant for individual months, except for water temperatures in May, during which burned lakes were 1.57°C warmer than control lakes (K-S $p = 0.02$) (Tables S3 and S4 in Supporting Information S1, Figure 3h). However, there were noteworthy seasonal dynamics for chlorophyll-a (Table S3 in Supporting Information S1, Figure 3f). Chlorophyll-a was greater in burned lakes from May-August, with peak differences in July (76% and 79% for drainage and isolated lakes, respectively). Conversely, September chlorophyll-a was 52% and 50% lower in burned drainage and isolated lakes compared to their respective control groups. These late-summer declines coincided with seasonal highs in TP, TN, and DOC, and seasonal lows in water clarity for burned drainage lakes and respective seasonal highs and lows for DOC and water clarity in burned isolated lakes (Table S3 in Supporting Information S1).

3.2. Water Quality Along Wildfire Disturbance Gradients

Water quality relationships with wildfire were strongest for TP, which was positively and linearly correlated with $\%WSBurnHS_{veg}$ (Adj $R^2 = 0.76$, $p = 0.01$) (Figure 4a). Other water quality relationships with wildfire were considerably weaker and often nonlinear. TN and DOC appeared to increase with %ShoreBurn until approximately 50%, but the curves flattened and declined slightly thereafter, resulting in marginally significant relationships (TN: Adj $R^2 = 0.33$, $p = 0.09$, DOC: Adj $R^2 = 0.49$, $p = 0.09$) (Figures 4b and 4c). Relationships between wildfire and pH, TSS, chlorophyll-a, and water clarity were comparatively weaker and all nonsignificant (Figures 4d–4g). The relationship between TSS and $\%ShorelineBurnHS_{veg}$ appeared linear and marginally

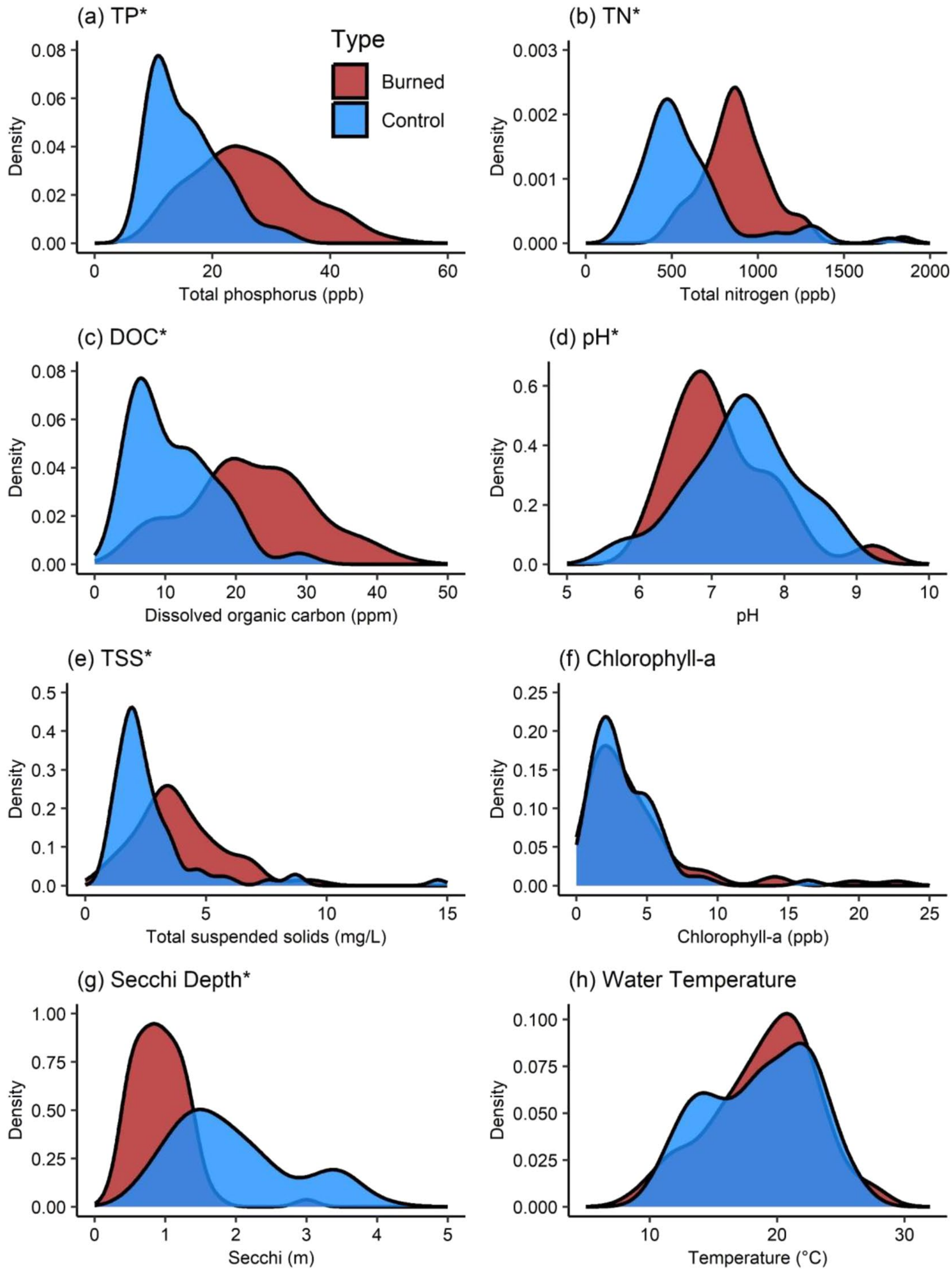

Figure 2. Water quality in burned versus control lakes (May–September 2022 combined data). * indicates significant differences from Kolmogorov-Smirnov tests.

significant ($p = 0.06$), but poor model fit (Adj $R^2 = 0.18$) suggests a weak relationship. Surface water temperatures were negatively, linearly correlated with %WSBurn (Adj $R^2 = 0.55$, $p = 0.08$), but the slope was nearly flat, reflecting minimal surface temperature variability among burned lakes (Figure 4h). In summary, water quality responses were often not proportional to wildfire disturbance in the first year following wildfire, with the notable exception of TP, which increased linearly with $\%WSBurnHS_{veg}$.

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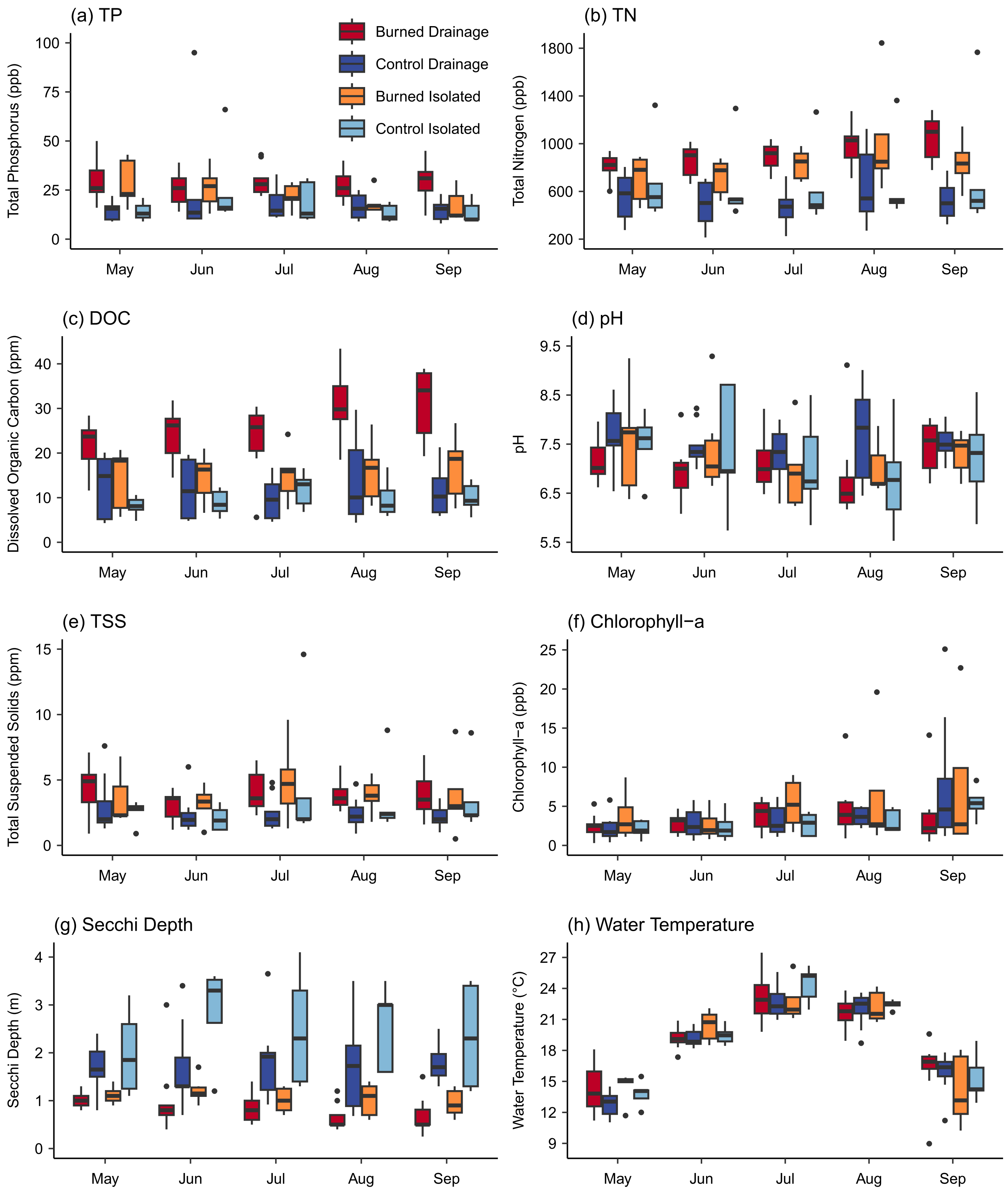

Figure 3. Water quality across burned versus control groups, months, and hydrologic connectivity classes.

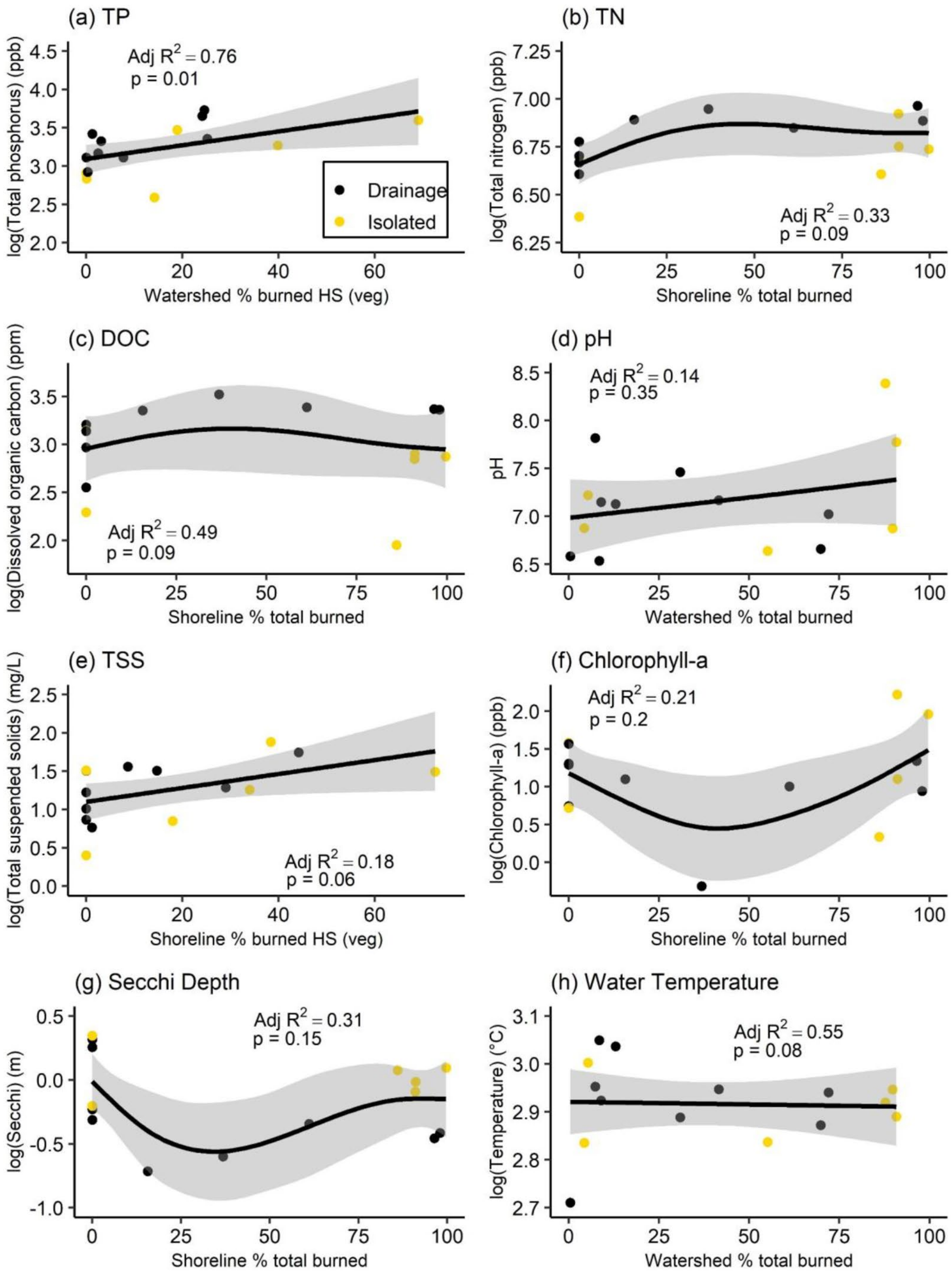

Figure 4. Water quality responses along wildfire disturbance gradients. Thick black lines represent generalized additive models between each water quality variable (May–September averages) and corresponding strongest wildfire disturbance predictors (by adjusted R^2). Gray areas represent 95% confidence intervals and p-values approximate significance of smooth terms. veg = vegetation.

3.3. Variance Partitioning

Wildfire variables explained the most variation in TP among water quality variables. %ShoreBurnHS$_{veg}$ explained more variation in TP (39.6%) than did other lake and watershed variables (Figure 5e). TSS (4.1%–19.6%) and TN (3.1%–16.3%) were next most explained by wildfire variables, with %ShoreBurnHS$_{veg}$ explaining the most variation in TSS (Figure 5e) and %ShoreBurn for TN (Figure 5d), respectively. Wildfire variables typically

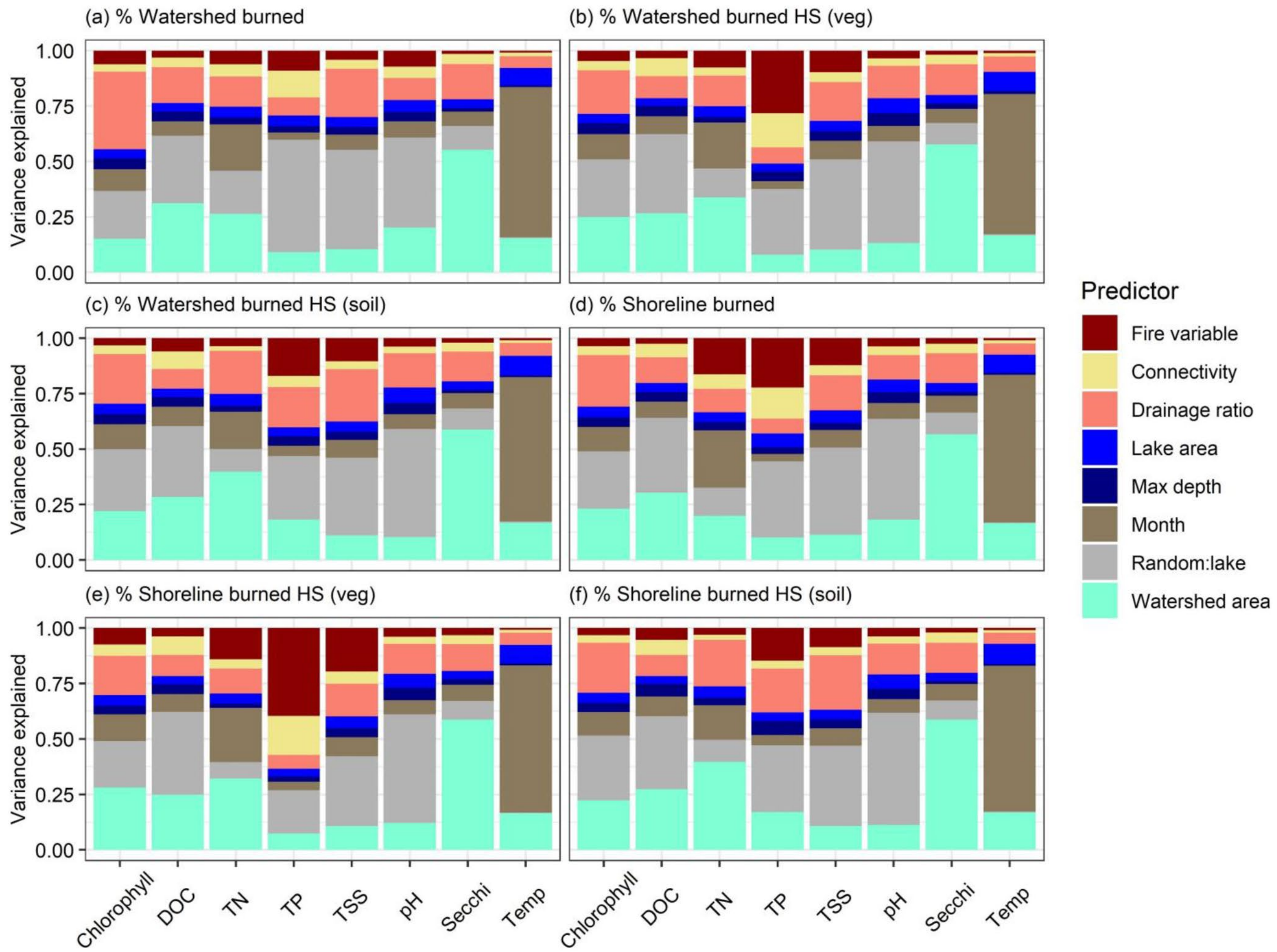

Figure 5. Variance partitioning analysis for water quality variables (May–September averages). Stacked bars represent relative variation explained. HS = high-severity, veg = vegetation.

explained <10% of variation in other water quality variables, including 1% or less for water temperature. Moreover, %WSBurn often explained the least variation in water quality (<10% for all variables except TP), compared to high-severity and shoreline burn variables. However, watershed area and drainage ratio consistently explained more variation in all other water quality variables than did wildfire variables, especially for water clarity. Nonetheless, the case of TP and high-severity shoreline burns shows that wildfires can exceed the influence of other water quality drivers under some circumstances.

4. Discussion

By monitoring a broad suite of indicators throughout the open-water season, we demonstrated significant effects of wildfire on TP, TN, DOC, TSS, pH, and water clarity. Effects were particularly strong for drainage lakes and can be persistent or cumulative throughout the first year post-wildfire. The marked responses of drainage lakes are perhaps unsurprising given that previous studies have shown that runoff and streamflow often increase following wildfire due to reduced evapotranspiration, plant nutrient uptake, canopy interception of precipitation, and soil water absorption (Williams et al., 2022). Ash and smoke may also deposit nutrients, materials, and ions into lakes and tributaries (Scordo et al., 2021), but the heightened responses of drainage lakes suggest greater contributions from watershed runoff in our study. Due to faster flushing rates in drainage lakes, however, it is possible that water quality differences due to wildfire could be delayed or more persistent in isolated lakes despite being initially smaller, underscoring that additional years may be necessary to observe post-wildfire ecosystem dynamics in isolated lakes.

Among our most notable results were the lack of post-wildfire changes in chlorophyll-a despite significant increases in TP and TN in both burned drainage and isolated lakes. Although this is consistent with some previous studies (Allen et al., 2003; McEachern et al., 2000), chlorophyll-a was marginally higher in burned lakes in all months except September. However, DOC peaked in September in both burned drainage and isolated lakes, suggesting that accumulating DOC and light limitation may eventually nullify nutrient increases. Large late-summer precipitation events (Figure S5 in Supporting Information S1) (≥97.5th percentile; NOAA, 2023) may explain corresponding pulses in DOC and nutrients, particularly considering our low topographic complexity and increased soil hydrophobicity post-wildfire (Mataix-Solera et al., 2011), but the burn's patchiness (Figure 1, Figure S4 in Supporting Information S1) suggests considerable spatial heterogeneity in carbon and nutrient runoff potential. Furthermore, lesser post-wildfire DOC and nutrient responses in isolated lakes suggest that isolated lakes may be less immediately sensitive to large precipitation or snowmelt events, but responses could increase in subsequent years. Nonetheless, it is difficult to explain complex dynamics between nutrients and carbon in burned watersheds given heterogeneity in burn severity, vegetation, and soil characteristics (Agbeshie et al., 2022) using data from our study.

Unlike previous studies that simply compared burned and control groups, we analyzed water quality responses along gradients of watershed and shoreline burn extent and severity and showed that TP increased linearly with $\%WSBurnHS_{veg}$. Additionally, $\%ShoreBurnHS_{veg}$ explained more variation in TP than lake and watershed variables known to influence water quality, indicating that wildfires can sometimes override other water quality drivers. Wildfire mineralizes soil organic P into more soluble inorganic P (Burd et al., 2018), which may help explain strong wildfire-TP relationships. However, lake and watershed variables typically explained more variation in other water quality variables than did wildfire variables, suggesting that ecological context mediates lake responses to wildfire. Taken together, our results highlight the importance of burn extent, pattern, and severity, lake and watershed context, and how certain water quality variables (e.g., TP) and lake types (e.g., drainage lakes) are particularly sensitive to wildfires.

4.1. Wildfire in Northern Minnesota: Historical Context and Future Outlook

Northern Minnesota forests represent fire-dependent ecosystems, meaning that fires historically played important roles in forest composition, pattern, and structure (Frelich et al., 2021; Heinselman, 1973). Prior to the early 20th Century, northern Minnesota forests historically experienced large, stand-replacing fires approximately every 25 years, but also smaller and more frequent, low-severity surface fires every 5–10 years that together produced and maintained a mosaic of forest patches of varying composition, age, and size (Heinselman, 1973; Kipfmueller et al., 2017, 2021). Notably, many of the well-documented historical phenomena that have contributed to the recent increase in western North American wildfires, including fire suppression, cessation of ignitions by Native Americans, and shifts toward larger, denser patches of fire-sensitive species have also occurred in northern Minnesota (Heinselman, 1973; Kipfmueller et al., 2017; Larson et al., 2021; Swain, 1973). Given the relative lack of recent wildfire, northern Minnesota and other lake-dense regions may be experiencing fire deficits and therefore could face more wildfires in the future (Parks et al., 2015), particularly as fire weather increases under climate change (Abatzoglou et al., 2019) and humans continue accidental ignitions (Balch et al., 2017).

4.2. Conclusions and Lighting a Path Forward

By conducting the largest-ever lake-wildfire study in an understudied, lake-dense region where wildfire was historically prevalent, we add to growing knowledge of lake responses to wildfire by highlighting the importance of burn pattern and severity, hydrologic connectivity, lake and watershed variables, and intra-annual water quality dynamics. Nonetheless, our lakes were shallow, high-DOC, oligo-mesotrophic, and macrophyte-dominated and our findings may not readily translate elsewhere. For example, mixed or weak algal biomass responses to wildfire may reflect bias toward high-latitude regions with carbon-rich soils. Moreover, wildfire-derived nutrients may be negligible for highly productive lakes (De Palma-Dow et al., 2022; Lewis et al., 2014). These studies suggest that clear, unproductive lakes could experience post-wildfire increases in primary productivity, but also that post-wildfire dynamics of nutrient and light limitation are important. Regardless, given local nuances, additional studies across ecologically diverse regions would further our understanding of why some lakes are particularly sensitive to wildfires. Our variance partitioning suggests that interactions among fire, lake, and watershed variables influence post-wildfire lake responses, so future studies might adopt a multi-scale perspective. Related, longer-term studies would also help track post-wildfire lake ecosystem recoveries and possible regime shifts, particularly considering that most previous studies lasted ≤3 years (McCullough et al., 2019). This collective knowledge will help scientists and managers better anticipate wildfire impacts on water quality, especially in regions dependent on lakes for drinking water, recreation, and other key ecological or cultural uses.

Data Availability Statement

Statistical analyses were performed in R version 4.2.1. Water quality, wildfire, and ancillary lake and watershed data and R scripts are available on Zenodo (McCullough et al. (2023); https://doi.org/10.5281/zenodo.8213144).

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