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Influence of barrens restoration treatments on soil carbon, nitrogen, and mercury pools and emissions

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Abstract

Currently barrens communities only represent about 1% of their original area in the Great Lakes region. To maintain or restore barrens vegetation, prescribed fire is often applied to limit the regeneration of undesirable species and shrubs. Vegetation community response is a combination of direct fire effects on the vegetation vitality and the indirect effect of soil nitrogen (N) loss that favors nutrient-poor adapted barren communities. In this study, we assessed forest floor and upper mineral soil (0–5 cm) pools of carbon (C), N, and mercury (Hg) before and after prescribed fire of the Moquah Barrens in northwest Wisconsin. Although we took measurements in four distinct cover types, we found no relationship between cover type and soil pools. Across all cover types, prescribed fire led to considerable emissions of C, N, and Hg in the forest floor but only Hg in the upper mineral soils (0–5 cm), presumably because maximum fire temperatures were met for Hg volatilization. We classified fire severity and soil surface temperatures at the quadrat scale, but no discernable relationships with emissions were observed. The lack of detectable relationships is likely the result of a mismatch between the scales of response variables and predictors. As a result, we calculated ecosystem-scale fire emissions based on the total area burned because we could not discern other smaller scale predictors. Overall emissions from dormant, spring season prescribed fires at the Moquah Barrens were approximately 11,000 Mg (5.5 Mg ha^{-1}) for C, 350 Mg for N (0.17 Mg ha^{-1}), and 4,500 g for Hg (2.3 g ha^{-1}).

1 | INTRODUCTION

Globally, barren communities are at peril from anthropogenic change. For example, the Great Lakes region has experienced a 99% decline in pine barren area compared to pre-settlement area (Wisconsin DNR, 2015). Barrens provide essential habitat for many endangered, threatened, and rare plant and animal species, which have experienced a similar decline, such as the silky prairie clover (*Dalea villosa*), Karner blue butterfly (*Lycaeides melissa samuelis*), and sharp-tailed grouse (*Tympanuchus phasianellus*).

Barrens are generally composed of a variety of vegetation communities that vary in structure, composition, and canopy cover. For example, pine barrens range from open-canopy prairies to pine and oak savannahs and closed-canopy forests (Jamison et al., 2023; Radeloff et al., 2000). Barren vegetation is generally controlled by the frequency of

Abbreviations: NPS, National Park Service.

fire, with more frequent fires leading to more open-canopy vegetation communities. However, the heterogeneous array of vegetation communities is what leads to a unique combination of various habitats necessary for species diversity.

Barren soils vary but are typically coarse textured, droughty, and low in nutrients and carbon (C) (Quigley et al., 2021). The nutrient poor soils maintain barren communities, but, in the absence of fire, nutrient accumulation may occur through mesophication and associated processes, facilitating development of fire-sensitive vegetation with greater soil nutrient demands (e.g., aspen species; Nowaki & Abrams, 2008). In the western Great Lakes region, barren communities occur on sandy outwash soils that resulted from meltwaters and subsequent deposition during the Wisconsin glacial period. Maintenance and restoration of these barren communities involves prescribed fire treatments to mimic natural fire processes that limit organic matter and associated nutrient accumulation in upper soils.

Utilizing fire to restore barrens communities leads to emissions of C, nitrogen (N), and mercury (Hg) that contribute to climate change (i.e., atmospheric CO_2) and decrease ecosystem productivity and fertility (N), and is a source of environmental pollutants Hg. Understanding the influence of prescribed fires on C cycles is critical because of the greenhouse gas feedback to climate cycles and important soil processes associated with organic matter. Soil N pools are both the long- and short-term control on vegetation response with prescribed fire, generally leading to an early increase and subsequent decline over time of available N and nitrophilic plant species (Clark et al., 2015). Finally, Hg is a pollutant that bioaccumulates in the aquatic food chain and ultimately in the fish that we eat and other consumers of contaminated aquatic fauna (Kolka et al., 2019).

Although the vegetation response to barrens restoration is fairly well documented (e.g., Copenheaver et al., 2000), soil response to restoration efforts has had little attention. Because the goal during barrens maintenance and restoration is to maintain soils at a low nutrient level, hot surface fires that burn the upper organic matter layer are encouraged since much of the nutrient pool is in the organic and upper mineral soils. While a goal of barrens restoration is to lower nutrients such as N, fires also notably contribute to emissions of C and Hg (Kolka et al., 2017; Lui & Shi, 2023; Obrist et al., 2018), as well as N (Alexis et al., 2007; Kolka et al., 2017; Wan et al., 2023). Fire emissions of carbon dioxide (CO_2) from Canadian wildfires in 2023 were >13% of emissions from all sectors in 2022 (https://climateinstitute.ca/; European Centre for Median Range Weather Forecasts, 2023). Global N-oxide emissions from fires represent about 15% of global N emissions (Denman et al., 2007), and similarly, global Hg emissions from fires account for approximately 18% of global emissions (Zhang et al., 2023). However, the emission outcomes of prescribed fire treatments to restore and maintain barrens that are likely less intense than wildfires are not well understood.

Core Ideas

- Imperiled barrens communities only represent a small area of their original distribution.
- As a result of the decrease in barrens habitat, associated fauna and flora are also in decline.
- Prescribed fire is used to maintain or restore barrens ecosystems.
- Fire leads to the changes in soil carbon, nitrogen, and mercury pools and leads to associated emissions.
- Emissions from the Moquah Barrens prescribed fires were minor and did lead to the goal of decreasing soil nitrogen.

Several studies have attempted to link emissions to either burn severity indices or soil temperature (soil heating). Although fire severity and soil heating are often associated with C emissions (or N, or Hg), most studies are the result of modeling efforts with limited focus on field-demonstrated relationships (e.g., Ghimire et al., 2012; Veraverbeke & Hook, 2013; Walker et al., 2020). Kolka et al. (2014, 2017) assessed fire severity following a wildfire in northern Minnesota, at both the soil sample scale (0.71 m^2) and plot scale (500 m^2) and found good C, N, and Hg emission relationships at the soil sample scale with fire severity but not at larger scales due to local fire heterogeneity. Similarly, Boot et al. (2015) found no relationship between soil C pools and a three-class fire severity classification following wildfires in Colorado. The relationship between severity indices and prescribed fire in barrens restoration has not been studied.

Prescribed burn characteristics like burn frequency or intensity (i.e., temperature) are often measured during fires but are rarely linked directly to emissions. Again, studies have modeled fire heating effects on soils and associated emissions, most notably with the FOFEM model (Brady et al., 2022; Webster et al., 2016). Only one study in the Amazon assessed soil temperature profiles during fire and found soil profile temperatures had little relationship with Hg emissions (Melendez-Perez et al., 2014). Indicators of soil temperatures during prescribed fires were related to subtropical soil C and N concentrations post fire (Alexis et al., 2007), but not emissions. Likewise, a study of pine barrens soil nutrients indicated some significant relationships between certain nutrient stocks and historic burn frequency (Quigley et al., 2020).

To determine the influence of barrens restoration across the range of barrens vegetation types on O horizon and mineral soil total C, N, and Hg, we established a study in the Moquah

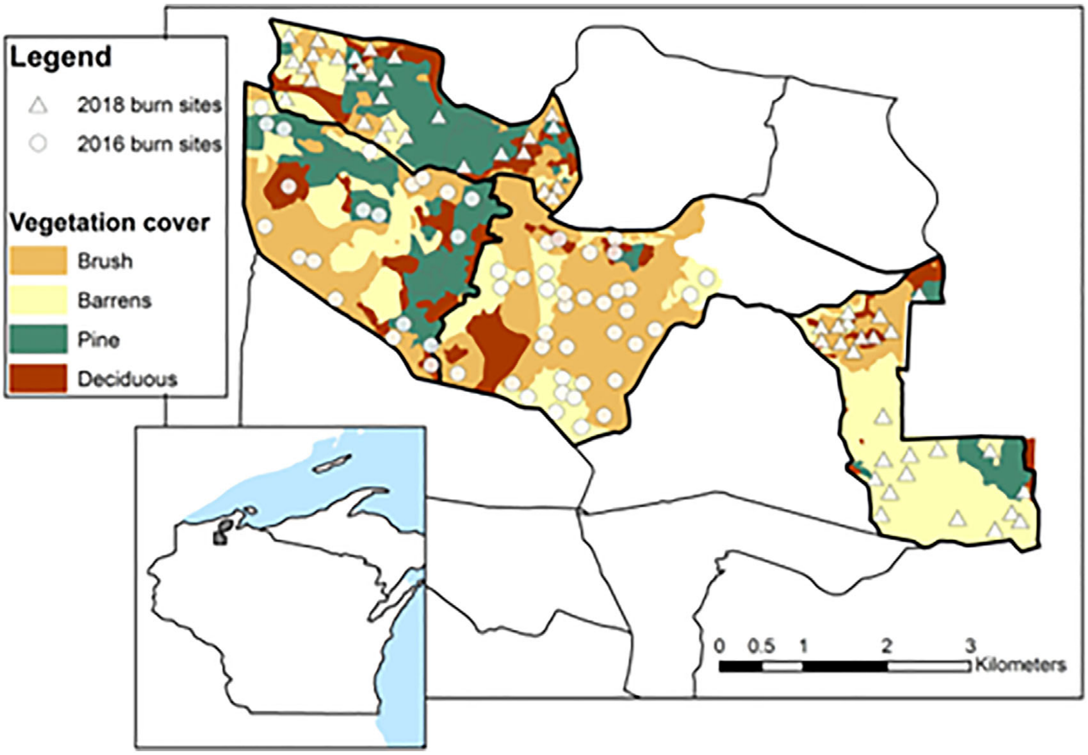

FIGURE 1 Map of the study area indicating the four vegetation cover types and our plot network (112 plots) pre- and postfire. Total area burned with prescribed fire during the study was 2034 ha.

Barrens in northwest Wisconsin on the Chequamegon-Nicolet National Forest. Moquah contains approximately 10% of Wisconsin's remaining pine barrens (Wisconsin DNR, 2015). The objectives of the soils research were to characterize the influence of fire on soil C, N, and Hg pools and associated emissions. In addition to estimating emissions, we investigated relationships between pools and emissions and three potential predictor variables: vegetation cover type, fire severity, and maximum soil surface temperatures during fire.

2 | SITE AND METHODS

2.1 | Study area

The study took place in the Moquah Wildlife Management Area (henceforth Moquah), in the Chequamegon-Nicolet National Forest in northwest Wisconsin (Figure 1). Moquah was established in 1970 and includes 10 management units encompassing approximately 6000 ha. Moquah has a mean annual temperature of 5°C and mean annual precipitation of 780 mm year^{-1}. Soils are well to excessively drained Spodosols developed on outwash plains and are classified as Vilas loamy sands and Sultz sands, both Entic Haplorthods. Topography ranges from flat to rolling hills (Quigley et al., 2019).

Vegetation cover in Moquah varies from open-canopy pine barrens to closed-canopy forest. Barrens communities are the result of a mosaic of open, shrubland, pine woodland, and deciduous forest. Shrublands consist of >50% cover of woody shrubs (*Amelanchier laevis* Wiegand, *Corylus cornuta* Marshall, *Corylus americana* Walter, *Salix humilis* Marshall, and others). Pine woodlands include thinned plantations of red pine (*Pinus resinosa*) and jack pine (*Pinus banksiana*) and sparse naturally occurring white pine (*Pinus strobus*). Deciduous forests are dominated by aspen (*Populus tremuloides* Michx. and *Populus grandidentata* Michx.), oak (*Quercus rubra* L. and *Quercus ellipsoidalis* E. J. Hill), and red maple (*Acer rubrum* L.) (Quigley et al., 2019).

2.2 | Study design

Experimental plots were installed following modified FIREMON protocols (Lutes et al., 2006) at 112 locations throughout four of the adjacent burn units (Figure 1). Plots were 20 m in radius (area = 1256.6 m^2) and contained several 1-m^2 quadrats utilized for soil sampling and for characterizing fire severity via visual estimates and classifying maximum soil surface temperature via pyrometers (see field sampling). Replicate plots spanned four vegetation cover types, including open barrens, brush, pine woodland, and deciduous forest, as well as brush additions and removals designed to create contrasts in fire severity and soil heating (Sturtevant et al., 2020). We established these plots in 2015 and 2016 as part of a broader study of soil heating during prescribed burns

(Quigley et al., 2019). Dormant season prescribed burns were conducted for two management blocks in May 2018. The two blocks burned in 2018 were last burned in 2014.

2.3 | Field sampling

Organic surface and mineral soil samples 1-year prefire and immediately (i.e., 1–2 days) postfire were sampled within each 1 m^2 soil sampling quadrat. The O horizon included forest floor and duff layers depending on the cover type and is referred to as "forest floor" in this study. The entire forest floor was removed from within a 30-cm diameter sampling ring before using a soil hammer bulk density sampler (0.079 cm^2 surface area) to remove a 10 cm deep mineral soil core, subsequently divided into an upper (i.e., 0–5 cm) and lower (5–10 cm) portion. We only analyzed the upper 5 cm of mineral soil for this study, as our previous research on wildfires in the region and others indicated little effect of fires on mineral soil pools (Kolka et al., 2017; Nave et al., 2011). Concurrently with soil sampling, we assessed burn severity within the soil sampling quadrat using the National Park Service (NPS, 2003) index. The NPS severity index is a substrate assessment including five qualitative classes, each assigned a numeric rating: "unburned" (5), "scorched" (4), "lightly burned" (3), "moderately burned" (2), and "heavily burned" (1) (NPS, 2003). A few days prior to prescribed burns, we installed aluminum tags (pyrometers) treated with a series of 9 Tempilaq (TEMPIL) temperature-indicating paints at 5 cm above the litter surface to approximate the maximum surface temperature reached during fires (Quigley et al., 2019). The paint tags were collected during soil sampling and assessed for paint melt color.

2.4 | Lab measurements

The forest floor and mineral soil samples were air dried, and mineral soils were passed through a 2-mm sieve before grinding. Both forest floor and mineral soils were ground with a stainless-steel Wiley mill. Samples were analyzed for total C and N concentrations on a LECO total elemental analyzer, with a separate subsample analyzed for total Hg concentration using a direct Hg analyzer (DMA-80, Milestone Inc.) using the United States Environmental Protection Agency Method 7473 (USEPA, 2009). We measured the volume and dry weight of the forest floor and mineral soils samples to calculate bulk density and to scale soil concentrations to soil pools.

2.5 | Data analysis

We modeled the response of C, N, and Hg pools in the forest floor and upper mineral soil (0- to 5-cm depth) to factors related to the restoration prescribed fire treatment: burn status (prefire and postfire), vegetation cover type category, fire severity category, and pyrometer temperature. Pre and postfire soil pool comparisons were made using paired *t*-tests and plotted via the "stat_compare_means" command in the ggpubr package in R (Kassambra, 2023; R Core Team, 2023). For the remaining predictor variables with ≥3 factor levels, we used analysis of variance (ANOVA) in base R. Where ANOVA indicated significant differences among treatment groups, we used post hoc Tukey's honestly significant difference (HSD) tests to identify pairwise differences between groups; we considered relationships significant when $\alpha < 0.05$. Within each horizon, total emissions of each element were calculated as the difference between prefire and postfire pools. For forest floor, we used linear regression (ordinary least squares) to determine whether emissions were a function of consumption.

3 | RESULTS

Vegetation cover was a poor predictor of forest floor C, N, and Hg pools (ANOVA $p > 0.05$), but paired *t*-tests indicated that forest floor pools of C ($t = -7.5$, $df = 98$, $p < 0.01$), N ($t = -5.9$, $df = 98$, $p < 0.01$), and Hg ($t = -4.1$, $df = 101$, $p < 0.01$) each varied significantly between pre- and postfire burn status across all samples. Forest floor C pools decreased by 47%, N pools by 40%, and Hg pools by 36% following prescribed fire (Figure 2a,c,e). In the forest floor horizon, C and N pools declined due to both mass loss (i.e., consumption) and overall decreased concentrations, whereas mass and nutrient concentrations remained stable in mineral soils with the exception of a small, yet statistically significant, reduction in Hg concentration (Table 1). Forest floor consumption explained approximately 50%–60% of variation in C, N, and Hg emissions (Table 2).

We found no differences in the 0- to 5-cm mineral soil layer for C and N between pre- and postfire ($p > 0.05$; Figure 3b,d), but mineral soil Hg pools were significantly lower following fire decreasing by 13% ($t = -2.0$, $df = 105$, $p = 0.04$; Figure 2). We also found no relationships between plot-scale vegetation cover type and the sample-scale C, N, or Hg emissions in the forest floor or 0- to 5-cm mineral soil layer.

NPS burn severity ratings were not clearly captured by specific pyrometer thresholds, and neither of these variables were related to C, N, and Hg remaining postfire or emissions from the forest floor and mineral soils. Although pyrometers with no paint melt were almost exclusively associated with an NPS 5 rating (unburned) and the majority of moderately burned (class 2) ratings were assigned to plots where aluminum melt occurred, NPS classes 3 and 4 (lightly burned and scorched) were ubiquitous among the pyrometer paints, and none of the postfire soil quadrats surveyed were rated as class 1 (heavily burned). Part of the reason for few relationships with pyrometers and burn severity rankings is they were not measured

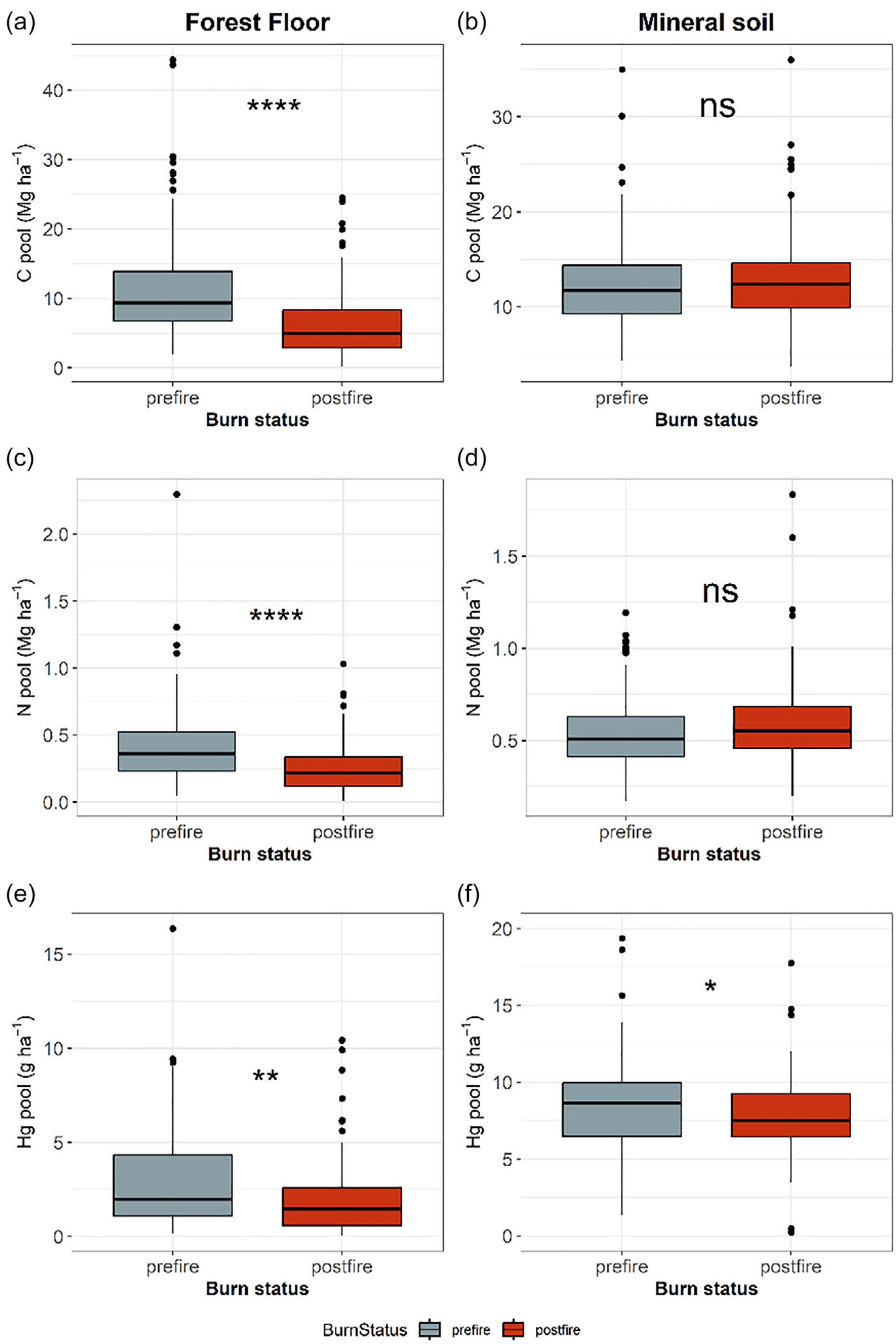

FIGURE 2 Comparison of C, N, and Hg pools pre- and postfire at the Moquah Barrens. Level of significance is indicated by asterisks (*$p \leq 0.05$, **$p \leq 0.01$, and ****$p \leq 0.0001$), with "ns" indicating not significant. $N = 112$ for each panel.

in same quadrant as the soils were sampled, and microsite variability in burn conditions likely led to few relationships.

4 | DISCUSSION

Few studies that have assessed C and N cycling following prescribed fire in barrens communities, and no studies have investigated the effect of fire (prescribed or wild) on Hg pools in barrens. Much of the research aiming to understand the effects of prescribed fire on barrens C and N cycling has been conducted in the Pine Barrens of New Jersey. The New Jersey Pine Barrens are composed of similar, low productive, sandy soils that are not of glacial origin but instead the product of sandstone weathering (Clark et al., 2015). Although considerable research has been done on ecosystem C and

TABLE 1 Mass density and elemental concentrations of pre and postfire forest floor and 0- to 5-cm mineral soil samples. Reported values are mean ± standard error.

Soil layer	Burn status	Mass per area (kg m^{-2})	% C	% N	Hg (ppm)
Forest floor	Prefire	4.6 (0.4)	31.5 (1.0)	1.14 (0.04)	0.066 (0.003)
	Postfire	2.9 (0.2)	24.0 (0.9)	0.99 (0.04)	0.058 (0.003)
Mineral soil	Prefire	47.1 (0.8)	2.76 (0.12)	0.12 (0.01)	0.020 (0.001)
	Postfire	47.0 (0.7)	2.89 (0.11)	0.13 (0.01)	0.017 (0.001)

TABLE 2 Summary statistics for ordinary least squares regression between the total emissions of each element and forest floor consumption.

Element	R^2	Slope	F-statistic	p
C	0.52	1.37	$103_{1,97}$	<0.01
N	0.56	0.06	$124.8_{1,97}$	<0.01
Hg	0.59	0.52	$144.8_{1,100}$	<0.01

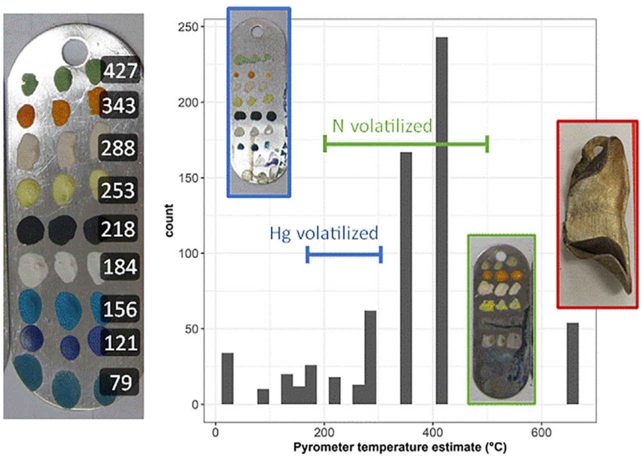

FIGURE 3 Distribution of pyrometer-estimated temperatures, showing volatilization range for Hg and N (Biswas et al., 2007; Bodí et al., 2014), as well as field-collected pyrometers associated with specific temperatures. Pyrometer from an unburned quadrat is shown on the left for reference. Hg volatilization (blue range) generally occurs between 180 and 300˚C; the white paint (fourth row from bottom) melts at 184˚C. N volatilization (green range) begins to occur at 200˚C, as indicated by melting of the black paint (middle row). The far right box (red) shows a melted aluminum pyrometer, indicating that temperatures exceeded 660˚C.

modeling N cycles in the New Jersey Pine Barrens (Lucash et al., 2014), little work has addressed the impact of fire specifically on soil pools. Combined estimates of the litter + understory C consumption of ∼4.7 Mg ha^{-1} are similar to the 5.5 Mg ha^{-1} emitted from the Moquah fires for forest floor (Clark et al., 2015). Studies on finer textured barren soils in Kentucky indicate increases in upper mineral soil C following prescribed fire but forest floor pools were not measured (Rhoades et al., 2002). It appears that no studies have investigated field-based measured N emissions from forest floor or mineral soils resulting from barrens-related fires.

Similar to C and N, Hg pools decreased in the forest floor but also in the upper mineral soils. Although the combustion and volatilization of the forest floor is the main vector for emissions, volatilization of Hg in the upper mineral soils indicates soil temperatures reached or exceeded approximately 180˚C when Hg volatilization begins to occur (Biswas et al., 2007). Our pyrometer temperatures at the soil surface exceed 180˚C approximately 90% of the time (Figure 3), however, we did not measure maximum temperatures in the 0- to 5-cm mineral soil layer to confirm. Although differences in the forest floor layer were more pronounced, the Hg emissions from the 0- to 5-cm mineral soil layer (1.2 g ha^{-1}) were comparable with the forest floor layer (1.1 g ha^{-1}) because of the much greater Hg in mineral soil pools (∼9 g ha^{-1} in mineral soils, 3 g ha^{-1} in the forest floor) (Figure 2). Volatilization of N begins at about 200˚C, but we did not see a mineral soil change postfire. That combination of results indicates that perhaps mean temperatures in the 0- to 5-cm mineral soil depth met or exceeded 180˚C frequently but not 200˚C.

C and N losses resulting from prescribed fire vegetation treatments at Moquah led to little change in mineral soil associated with C and N pools, similar to other studies in different ecosystem types (Kolka et al., 2017; Mitchell et al., 2012; Nave et al., 2011). Even during severe wildfires, changes in mineral soils pools are uncommon, with the bulk of the changes occur in the upper organic horizons. Moreover, vegetation cover type, fire severity classification, and pyrometer maximum temperature class were not related to C, N, and Hg pools or emissions. The lack of a relationship appears surprising given the range of fire severity and pyrometer temperatures across the range in vegetation treatments. However, as shown in our previous studies, applying severity classes at larger than the soil sampling scale (1 m^2 vs. 0.079 m^2) leads to errors associated with fire heterogeneity (Kolka et al., 2017). At Moquah, we saw similar results that indicate fire severity class at the 1 m^2 quadrat scale had no relationship with soil C, N, and Hg postfire at the forest floor/soil sampling ring scale (0.079 m^2) embedded in the quadrant. Similarly, pyrometer temperatures measured at the center of the quadrat do not overlap post burn soil sampling ring location. Because we could not distinguish emissions based on vegetation cover, fire severity, or pyrometer temperature, we can assume emissions are similar across the Moquah Barrens management units. Given the total area management units treated with the 2016 and 2018 dormant season prescribed fires, approximately 11,000 Mg of C (5.5 Mg ha^{-1}), 350 Mg of N (0.17 Mg ha^{-1}), and 4500 g (2.3 g ha^{-1}) of Hg were liberated to the atmosphere.

5 | CONCLUSIONS

Using prescribed fire to maintain and restore imperiled barrens communities leads to emissions of C, N, and Hg. We found that prescribed fire decreased C, N, and Hg pools in the forest floor but did not have an impact, with the exception of Hg, in the upper mineral soils, similar to what other studies have found. It appears soil temperatures in the 0- to 5-cm mineral soil layer met or exceeded 180˚C, a temperature that volatilizes Hg, but likely did not exceed 200˚C as we saw no N volatilization response.

Overall, emissions of C from the prescribed dormant season fires were relatively minor when compared to 2021 emissions for the state of Wisconsin. Moquah prescribed fires accounted for about 0.03%, 1.4%, and 1.3% of C, N, and Hg emissions, respectively, when compared to state emissions (https://www.dhs.wisconsin.gov/epht/toxicair.htm). Although emissions from the Moquah Barrens prescribed fires investigated here are relatively minor when compared to state-level emissions, prescribed fire is a critical management tool that is used frequently at Moquah as well as across the region to meet forest management and restoration goals. The number of prescribed fires over time should be considered when evaluating long-term emissions. If enhancing or not negatively impacting ecosystem C storage is a management goal, the use of prescribed fire needs to be considered as part of a broader or landscape approach to managing C, as prescribed fire leads to the ecosystem being a net source of C to the atmosphere during the fire year. Also, the loss of N is a goal to restore barrens communities, however, losses of forest floor nutrients through prescribed fire emissions in nutrient demanding ecosystems could present long-term productivity issues. In the case of the Moquah Barrens, prescribed fire did release substantial N that presumably will lower future soil fertility and counteract the mesophication process to help maintain and restore barren ecosystems.

AUTHOR CONTRIBUTIONS

R. K. Kolka: Conceptualization; funding acquisition; investigation; methodology; project administration; supervision; writing—original draft. **K. M. Quigley**: Data curation; formal analysis; investigation; methodology; project administration; writing—review and editing. **J. R. Miesel**: Conceptualization; funding acquisition; investigation; methodology; project administration; supervision; writing—review and editing. **M. B. Dickinson**: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; writing—review and editing. **B. R. Sturtevant**: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; supervision; writing—review and editing. **C. C. Kern**: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; supervision; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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