Mountain Pine Beetle and Algae Blooms in Northwest Wyoming Sub Alpine Lakes

by

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Dedication

To my late grandfather, William George James Sr., seven years later and I have never regretted choosing Michigan.

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Abstract

Mountain Pine Beetle (MPB) is a tree pest native to North America that has led to the death of up to 90% of conifers in some mountain regions. In concert with MPB infestations, there has been an increase in algae blooms in historically oligotrophic mountain lakes. This study sought to assess the impact of MPB-induced tree mortality on soil and water nutrient concentrations, as well as the frequency and severity of algae blooms. During July and August of 2023, tree mortality estimates and soil and water samples were collected from 8 sub-alpine lakes in northwestern Wyoming. Tree mortality estimates were paired with soil nitrogen and phosphorus concentrations to assess patterns of potential nutrient loading into the lakes of interest. Soil nutrient concentrations show no significant relationship with MPB-induced tree mortality, which may point to an interaction between local geology and climate change playing a greater factor in facilitating the algae blooms observed in this region.

Introduction

Mountain Lakes

High elevation mountain lakes are sentinels of climate change, providing valuable paleoclimate records and capturing anthropogenic alterations to biogeochemistry, biology, and pollution (Moser et al., 2019; Schindler, 2009). Generally, these lakes are less subject to direct human perturbation and disturbance, which makes them ideal indicator environments and areas for paleoclimate study. Since the industrial revolution, these lakes have seen drastic changes in aquatic community assemblage (Ernst et al., 2009; Salmaso, 2010) and nitrogen balance due to exogenous atmospheric nutrient deposition (Moser et al., 2019). However, in and around the northern Rocky Mountains, most of these lakes have historically remained oligotrophic (Miller, 1995) likely due in part to comparably low terrestrial inputs of nutrients, positioning at or near the head of watersheds, and generally dimictic mixing regimes. Since 1950, diatom and cyanobacterial blooms have been observed more commonly in the eastern Rockies (Baron et al., 2021) with more dramatic shifts since the 1990s throughout the North American West as these lakes potentially move towards eutrophication (Oleksy et al., 2020). These shifts in productivity may pose risks to downstream drinking water quality, as well as negatively impact fisheries and tourism.

Sub-alpine lakes in the Southern Region of the Greater Yellowstone Ecosystem have experienced increased occurrence of harmful algae blooms (HABs). In the Greater Yellowstone Ecosystem, little attention has been given to the potential linkage between MPB-induced tree mortality and algal blooms in neighboring water bodies. While some studies have identified planktonic species in sediment cores (Spaulding et al., 2015) or via microscopy (WYDEQ, 2023) few have taken advantage of amplicon sequencing or metagenomics in order to evaluate planktonic assemblages in these lakes. This study focuses primarily on the Brooks Lakes Region in northwestern Wyoming, which is a tributary to the Wind River that supplies water to nearby Dubois, Wyoming. Continued monitoring in this region has found near annual blooms in some remote mountain lakes and potentially harmful concentrations of the hepatotoxins microcystin and nodularin (WYDEQ, 2023). HABs in Brooks Lake were originally attributed to mishandling of wastewater by nearby Brooks Lake Lodge (Korshmrl, 2017), but when similar HABs were documented in lakes higher in the watershed hypotheses shifted towards local phosphorus rich geology, changes in climate, or disturbance in the local watersheds.

Mountain Pine Beetle

Mountain pine beetle (*Dendoctronous Ponderosae,* MPB) is a tree pest endemic to North America and sporadic source of disturbance throughout the Rocky Mountains. Infestations by MPB have been linked to shifts in soil and aquatic biogeochemistry (Clow et al., 2011) and have negatively impacted drinking water facilities (Brouillard et al., 2016; Mikkelson et al., 2013). Almost the entirety of MPB's life cycle is spent within cambium of host *Pinus* species until reaching maturity—emerging to search for another host tree. Maturing beetles feed on the vascular tissues of their hosts, eventually preventing flow of water and nutrients to the tree canopy. This leads to the reddening (red phase) and senescence (grey phase) of needles. Historically, outbreaks have been limited in distribution due to overwinter population losses with survivorship and population size being determining factors in outbreak severity (Lewis et al., 2010; Règnière & Bentz, 2007). Elevated mean temperatures due to climate change have increased overwinter survivorship and expanded the elevational range of MPB into forests less adapted to repelling infestations (Larson, 2011). From 2003 to 2008, MPB was responsible for the death of nearly 500,000 acres of white bark pine (*Pinus albicaulis)* and other 5 needle pines (Gibson & Jorgensen, 2008) and has recently expanded beyond its historic geographical and climatic range barriers (Giroday et al., 2012).

MPB has been a widespread and potent disturbance in the Greater Yellowstone Ecosystem, with periodic infestations being a significant source of *Pinus* mortality (Bockino & Tinker, 2012; Logan et al., 2010; Macfarlane et al., 2023). In the 1930s, a large outbreak of MPB in the region was thought to pose a threat to all white bark pines. The elevational range of MPB has expanded due to warming temperatures resulting from climate change (Cullingham et al., 2011; Giroday et al., 2012; Logan et al., 2010), which has led to recent devastation of higher-elevation tree species such as white bark pine (Macfarlane et al., 2023). In the Greater Yellowstone Ecosystem, the most recent outbreak of MPB began in 1999 and has had moderate or severe impacts on *Pinus* species survivorship in 80% of watersheds in the region (Macfarlane et al., 2023).

Throughout the Rocky Mountains, this most recent MPB infestation has had varied impacts on terrestrial and aquatic biogeochemistry. In predominantly lodgepole pine (*Pinus contorta)* forests in west central Alberta, Cigan et al. (2015) found that litter inputs rates of NH_4^+, NO_3^-, and PO_4^- to soil increased with MPB-caused tree mortality. Additionally, concentrations of NH_4^+ continued to increase for 4 years following infestation (Cigan et al., 2015). Similar results have been found in Colorado, with elevated NO_3^- and NH_4^+ concentrations in soils following MPB infestation (Clow et al., 2011).

Despite the extensive disturbance to high elevation forests in the Greater Yellowstone Ecosystem since 1999, there have been few studies assessing how it has impacted biogeochemistry and high elevation freshwaters. This thesis seeks to evaluate the current extent of tree mortality across eight high elevation lake watersheds and connect this widespread disturbance with alterations in soil chemistry and planktonic community composition.

Due to its prolific impact on tree communities, I hypothesize disturbance by mountain pine beetle may reduce vegetative uptake of limiting nutrients and increase nutrient export to nearby waterbodies. This is an application of the nutrient retention hypothesis put forward by Vitousek & Reiners (1975). In the Rocky Mountains, soil moisture and concentrations of N and P to increase under predominantly grey phase stands (Cigan et al., 2015; Clow et al., 2011).

Methods

Study Sites

Three lakes in Briger-Teton and five lakes in Shoshone National Forests were sampled to evaluate the impact MPB infestation may have on soil and freshwater nutrient regimes and freshwater microbial community assemblage. The lakes in the Bridger-Teton National Forest were the Lower Toppings Lake (LTL), Leidy Lake (LeL), and Lost Lake (LoL). In the Shoshone National Forest Upper Jade Lake (UJL), Lower Jade Lake (LJL), Upper Brooks Lake (UBL), as well as the Northwest and Southeast Kissinger Lakes (KLNW; KLSE) were sampled (Figure 1). These lakes were selected due to access and to represent a range of severity in MPB infestation. LTL, LeL, and LoL were included as well as to compare against those within the Brooks Lake watershed and determine whether MPB is facilitating the algae blooms previously observed in the Brooks Lakes Basin. Additionally, all lakes included in this study are at or near the top of their respective watersheds—the only exceptions being the LTL, LJL, UBL, AND KLNW which receive inputs from other lakes included in this study[1].

Materials and Methods

Tree Mortality

Tree mortality was measured across five 225 m^2 quadrats within each watershed. Within each plot, the diameter at breast height (DBH) was measured for all trees with DBH > 4cm. Additionally each tree was categorized as living (healthy, displaying little to no signs of

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[1] Lower Toppings Lake is fed by Upper Toppings Lake, which was not included in this study.

infection), dead not due to MPB (windfall, crowding, etc.), or dead due to MPB. Trees were categorized as dead due to MPB if egg and larval galleries were visible in exposed sapwood or when bark was removed with a knife. The diameter of all trees within each quadrat was measured and summed for each plot and per category in each plot. These totals were averaged by watershed, with the average values used to estimate basal area (m^2/ha) and the proportion of deceased trees.

Soil Chemistry

Soil samples were collected 20 m from shore at depths of 15 cm to 25 cm in mineral soil within or near one of the overstory quadrats. Once collected, soil samples were dried under sunlight within 48 hours. Soil samples were homogenized to <2 mm particles with a sieve before inorganic nitrogen was extracted. Inorganic nitrogen was extracted using a 2 mL:1 g ratio of 2 M KCL and air-dry soil. Samples were placed on an orbital shaker for 30 minutes (Bremner, 1983), filtered (< 2.5μm), and filtrate was stored at -20°C. NH_4^+ and NO_3^- were measured using a Seal Analytical AQ2 Discrete Analyzer. Orthophosphate was extracted using the Bray-Kurtz P1 extraction solution (Pierzynski, 2000) and measured using a molybdenum blue colorimetric reagent (Pierzynski, 2000) on a spectrophotometer at a wavelength of 882 nm. After colorimetric determination of N and P concentrations, they were converted to mg/kg dry soil. Concentrations of N and P were then plotted against total tree mortality in the associated plot. Linear models were constructed for both N and P and their significance was assessed using a T-Test.

Results

Tree Mortality

The legacy of the most recent Greater Yellowstone outbreak of MPB is still present in the forest of the region. No red-phase (recently attacked) trees were present in any of the plots across any of the lakes. Additionally, in all the sampled watersheds besides LTL, more than 50% of stand basal area was made up of grey-phase snags (deceased trees, devoid of needles) on average (Table 1). The greatest impact was seen in KLNW (82%), UJL (82%), and KLSE (80%) where nearly all standing biomass is comprised of snags (Table 1). In six of the studied watersheds (LeL, LoL, UJL, LJL, KLNW, KLSE), snags showing signs of MPB infestation made up more than 50% of basal area on average (Table 1). Across all lakes more than 50% of standing snags showed signs of MPB infestation with LeL, UJL, KLNW, and KLSE having more than 90% of standing snags showing signs of infestation by MPB.

Soil Chemistry

No significant biogeochemical response to MPB induced tree mortality across the site or watershed level was detected. Assessments of soil inorganic N concentrations revealed nearly ubiquitously low concentrations of NH_4^+ and NO_3^- and no significant relationship ($p = 0.9414$) between MPB-induced tree mortality (Figure 2). Elevated inorganic-N concentrations were observed at one site at LeL and one site in the KLNW. Nonetheless, there was no significant relationship between local tree mortality and concentrations of inorganic nitrogen concentration in soil. Soil phosphorus similarly showed no significant relationship ($p = 0.1663$) to local tree mortality across the sampled soils (Figure 3). While some sites in the LeL and KLNW watersheds had elevated concentrations of phosphate (Figure 3), KLSE, which has a similar degree of tree mortality (Table 1) and is geographically near KLNW (Figure 1), had soil phosphate concentrations similar to the lower mortality LTL plots (Figure 2).

Discussion

While forests in northwest Wyoming have suffered grievous long-lasting disturbance due to MPB infestation, any associated decreases in vegetative uptake do not appear to have translated to longer term increases in soil nutrient concentrations. The lack of any significant relationship between MPB, soil inorganic N, and soil phosphate concentrations suggests that the harmful algae blooms observed in the Brooks Lake Region are not facilitated by MPB disturbance. Warming temperatures due to anthropogenic climate change and local geology may be larger drivers of the HABs observed in the Brooks Lake Region. Harmful cyanobacteria may have more days within their temperature optima to proliferate due to warmer temperatures and earlier ice out dates, whereas the phosphorus-rich volcanic surface and bedrock geology may be providing a limiting nutrient to the impacted waterbodies.

Tree Mortality

This study performed one of the first *in situ* surveys of MPB induced tree mortality in this region since Bockino & Tinker (2012). Their study surveyed the impact of MPB and non-native fungal pathogen white pine blister rust (WBPR, *Cronartium ribicola*) in white bark pine forests across the same southern area of the Greater Yellowstone Ecosystem. Below Teewinot, in Grand Teton National Park, Bockino & Tinker (2012) found 50-60% of trees were selected as hosts by MPB—this is significantly higher than the observed 30% mortality at nearby LTL (Table 1). However, underneath Mount Leidy, near LeL, 61-74% of trees had been colonized by MPB in 2012 (Bockino & Tinker, 2012), which is similar to the 69% mortality observed in that area through this study. Under Breccia Peak, near LoL, UJL, LJL, and UBL, between 77% and 82% of trees had been selected by MPB (Bockino & Tinker, 2012), which is again similar to proportions of tree mortality at UJL (82%) and LJL (79%) but higher than at LoL (60%), and UBL (62%). Since 2012 however, mortality has increased in this region from 45% of white bark pines (Bockino & Tinker, 2012) to 70% of trees in 2023. MPB infestation is clearly a driver of this severe disturbance as 67% of trees had been selected by MPB in 2012 (Bockino & Tinker, 2012) with 63% of trees being found to be deceased due to MPB across all sites in 2023 in this study. Given this, it seems likely that a very large proportion of trees selected for colonization by MPB in the Greater Yellowstone Ecosystem through this most recent infestation have perished. The similarity in proportions of trees selected by MPB in 2012 and proportion of trees mortality due to MPB suggests unusually high rates of successful colonization and MPB reproduction in the Greater Yellowstone Ecosystem.

The scale of tree mortality in the Greater Yellowstone Region poses numerous additional sociological and ecological problems as well. Seed cone viability in lodgepole pine (*Pinus contorta*) forests has been seen to decrease following MBP infestation (Rhoades et al., 2022). In Yellowstone National Park, MPB colonization from 1972-1975 increased the odds of a tree burning in the massive wildfires of 1988 (Lynch et al., 2006), whereas in Colorado and southern Wyoming lodgepole pine stands, MPB infestation did not impact the likelihood of forest fires (Kulakowski & Jarvis, 2011). Snags derived from this most recent infestation of MPB have likely been standing for between 10-25 years and may have a greater chance of burning in the event of widespread forest fire. These long-standing snags also may impact forest recovery. In stands with similar time since infestation, seed viability has decreased by 40% in the soil and crown seedbanks (Rhoades et al., 2022).

Lack of Soil Biogeochemical Response to Infestation

There was no observed biogeochemical response to MPB disturbance in the sampled watersheds. This is contrary to increases in NH_4^+ and NO_3^- concentrations under stands with more recent MPB mortality observed in the Rocky Mountains (Brouillard et al., 2017; Clow et al., 2011). While there was not an appreciable response in inorganic N, concentrations were similar to those under grey-phase stands in the White River National Forest (Brouillard et al., 2017). In sites through southern Greater Yellowstone Ecosystem with more than 60% tree mortality, inorganic N was greater than those with similar levels of mortality in the Fraser Experimental Forest (Trahan et al., 2015). However, concentrations of NH_4^+ and NO_3^- in this study were similar to those found in forests surrounding Yellowstone National Park and in the southern Bridger-Teton National Forest (Griffin et al., 2011). NO_3^- concentrations in streams have no significant response to MPB disturbance as well, with secondary successional plant uptake and the spatiotemporal variability in MPB infestations leading to compensatory responses in NO_3^+ uptake and dampening export (Rhoades et al., 2013).

Soil P responses to MPB disturbance are less studied compared to N response. Phosphorus concentrations were elevated in all but LTL and LJL compared to those measured in the Fraser Experimental Forest (Trahan et al., 2015). In the eastern region of the study (LoL, UJL, LJL, KLNW, KLSE) the presence of volcanic breccias and lahar deposits may be the source of elevated P in soil. Volcanic watersheds export more P compared to watersheds with non-volcanic geology (Dillon & Kirchner, 1975), but from this study any P flux from surface rock would not appear to be a significant enough source of P to facilitate HABs.

Limitations

The scope of this thesis was limited as it was a preliminary investigation into the potential of MPB facilitating algae blooms in northwest Wyoming. Analyses of soil biogeochemistry were limited to the predominant forms of N and P. In some MPB impacted forests, soil concentrations of organic forms of N and P as well as total N and P had more pronounced or significant responses to tree mortality (Brouillard et al., 2017). Additionally, sampling depth across sites was deeper than most comparable studies which creates uncertainty when comparing results. Despite these limitations, there is no evidence to suggest that MPB-induce tree mortality is linked to HABs via the increased in soil N and P concentrations and their export to local waterbodies.

Tables

Table 1. Average tree mortality, tree mortality due to MPB, and proportion tree mortality due to MPB ± SE. All lakes besides LTL had total tree mortality greater than 50%, and MPB accounted for 50% or more of total tree mortality across all lakes.

Lake	Average % Area Deceased	Average % Area Deceased MPB	% Area Deceased Caused by MPB
LTL	29.9 ± 5.8	13.8 ± 5.3	53.5 ± 15.9
LeL	68.7 ± 6.4	67.5 ± 6.0	98.4 ± 0.8
LoL	59.6 ± 8.4	53.3 ± 9.9	87.1 ± 6.6
UJL	81.6 ± 5.1	76.5 ± 5.2	94.4 ± 5.6
LJL	79.0 ± 5.4	68.5 ± 6.7	86.8 ± 6.2
UBL	61.6 ± 8.7	49.0 ± 8.8	79.3 ± 10.2
KLNW	82.1 ± 4.5	80.0 ± 3.7	97.8 ± 1.9
KLSE	80.2 ± 8.1	76.1 ± 7.9	95.1 ± 2.8

Figures

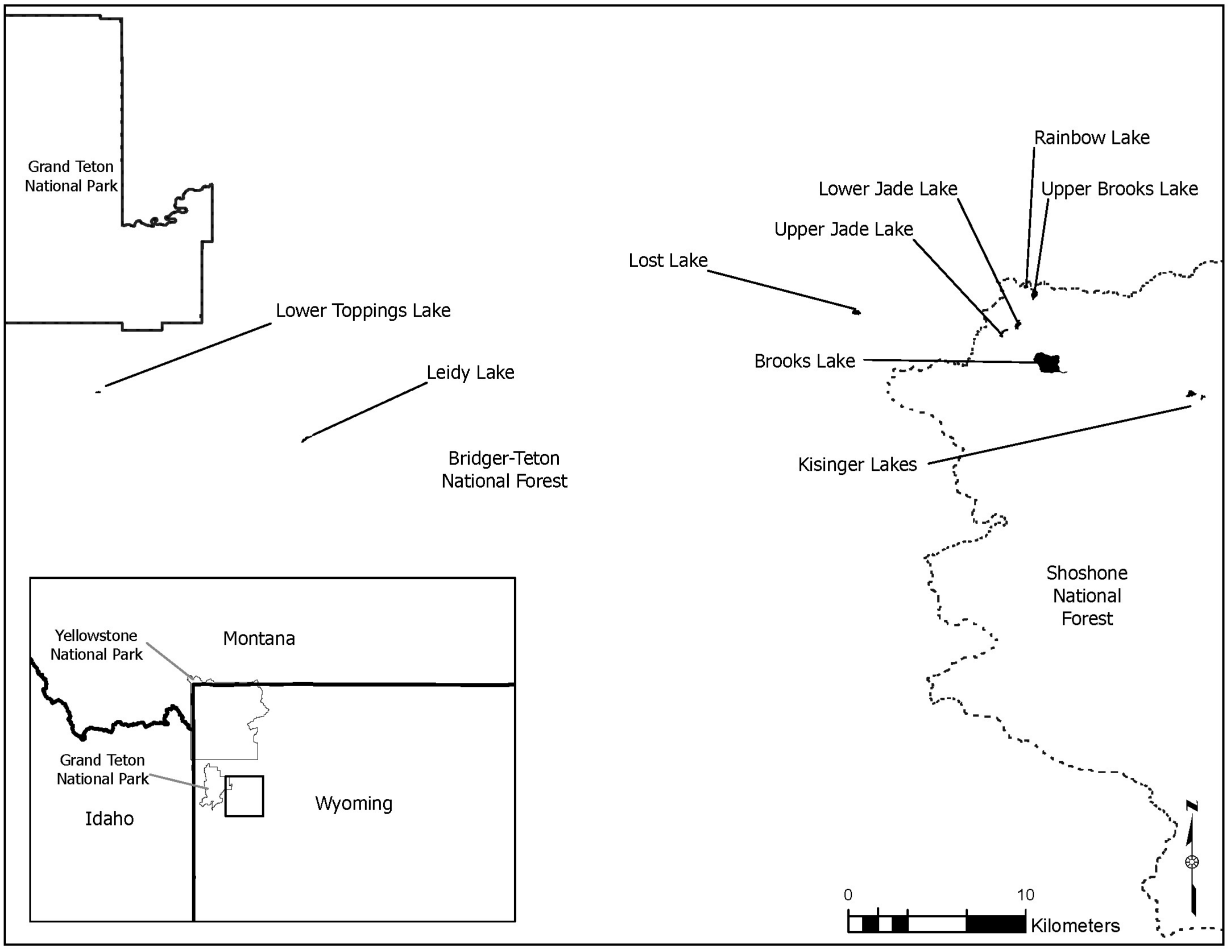

Figure 1. Location of the lakes and watersheds included within this study.

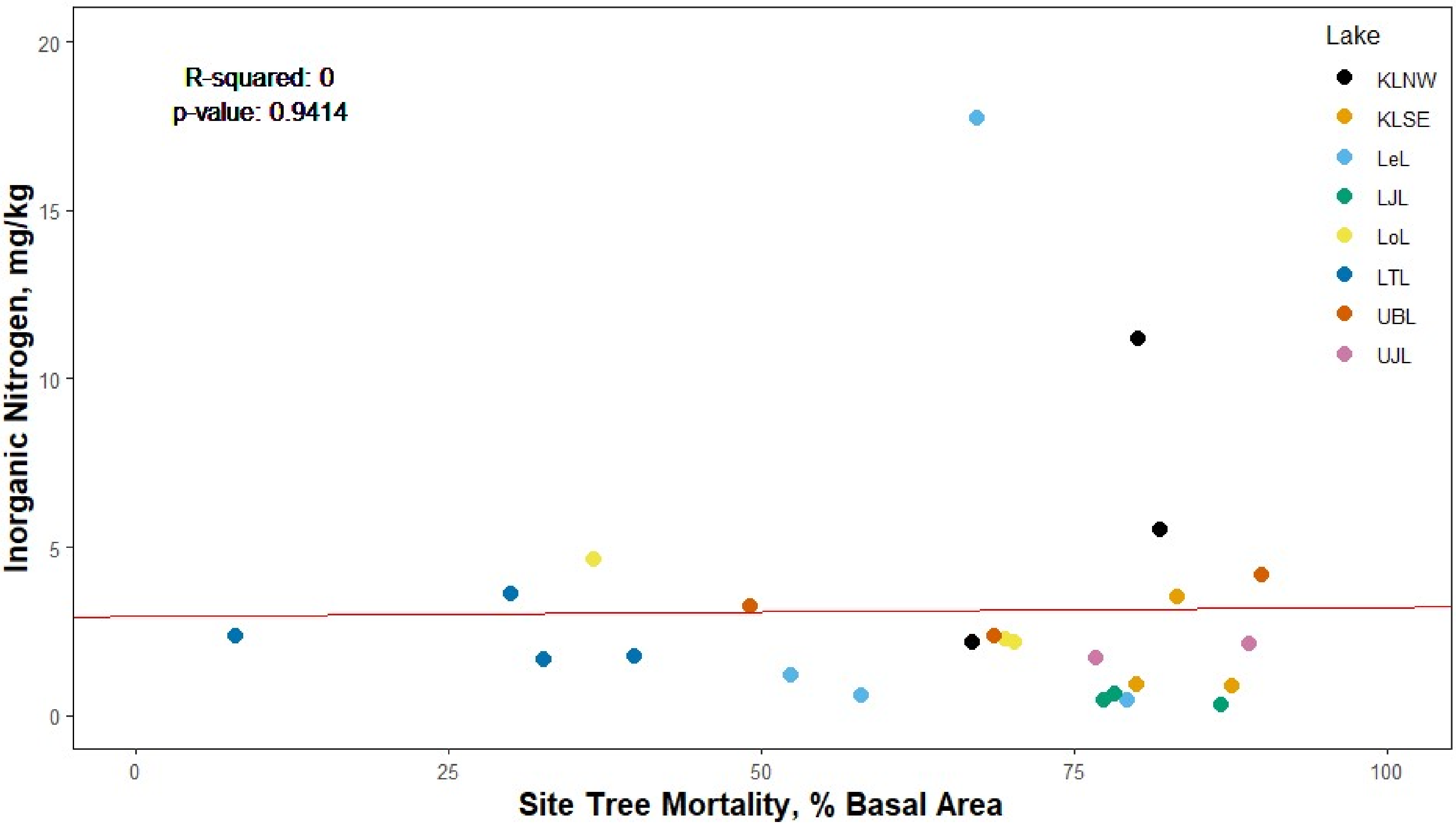

Figure 2. Inorganic nitrogen concentrations versus tree mortality across all soil sampling sites. There is no significant relationship ($p = 0.9414$) between MPB induced tree mortality and inorganic nitrogen

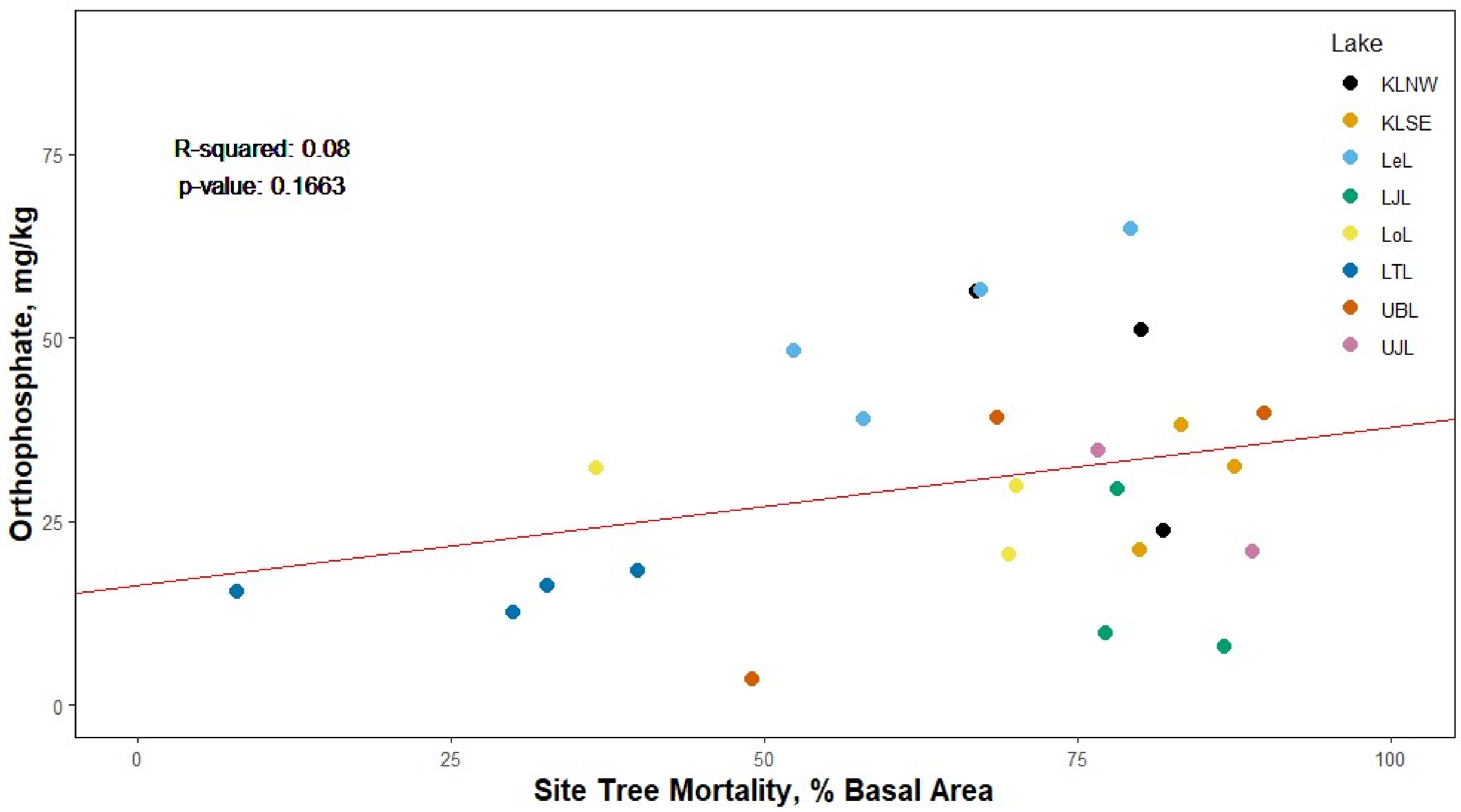

Figure 3. Orthophosphate concentrations versus tree mortality across all soil sampling sites. There is no significant relationship (p = 0.1663) between MPB induced tree mortality and orthophosphate concentrations

Appendix: Soil Sampling Information

Appendix 1. Soil sampling dates and locations

Lake	Site	Collection Date	Latitude	Longitude
Lower Toppings Lake	1	09-07-2023	43.741470	-110.481062
	2	09-07-2023	43.741621	-110.479613
	3	09-07-2023	43.742431	-110.479980
	4	23-07-2023	43.742293	-110.480630
Leidy Lake	1	16-07-2023	43.715990	-110.377658
	2	16-07-2023	43.716259	-110.377658
	3	16-07-2023	43.717511	-110.375657
	4	16-07-2023	43.719125	-110.373072
Lost Lake	1	11-07-2023	43.781290	-110.101741
	2	11-07-2023	43.780696	-110.100299
	3	11-07-2023	43.782096	-110.097515
	4	26-07-2023	43.783122	-110.100790
Upper Jade Lake	1	18-07-2023	43.771866	-110.025504
	2	21-07-2023	43.769605	-110.027609
	3	21-07-2023	43.772046	-110.026950
	4	21-07-2023	43.772822	-110.023414
Lower Jade Lake	1	18-07-2023	43.776731	-110.017195
	2	18-07-2023	43.777105	-110.018849
	3	18-07-2023	43.774431	-110.020513
	4	18-07-2023	43.773673	-110.018316
Upper Brooks Lake	1	13-07-2023	43.789603	-110.007623
	2	13-07-2023	43.792055	-110.008700
	3	13-07-2023	43.792694	-110.013420
	4	13-07-2023	43.789044	-110.012409
North West Kissinger Lake	1	19-07-2023	43.742101	-109.933347
	2	19-07-2023	43.740373	-109.934336
	3	19-07-2023	43.739844	-109.931763
South East Kissinger Lake	1	14-07-2023	43.738737	-109.927084
	2	14-07-2023	43.738872	-109.925603
	3	14-07-2023	43.740171	-109.925711

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