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PRESCRIBED FIRE EFFECTS ON WATER QUALITY VARIABLES IN THE
SOUTHERN APPALACHIAN REGION

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Forest Resources

by
Kipling B. Klimas
May 2020

Accepted by:
Dr. Patrick Hiesl, Committee Chair
Dr. Donald Hagan
Dr. Dara Park

ABSTRACT

The goal of this thesis was to fill a contemporary gap in empirical knowledge on prescribed fires effects on water quality in the forests of the Southern Appalachian Mountains. To accomplish this goal, I conducted an extensive literature review on fire effects on specific water quality variables: sediment yield and macronutrients, specifically nitrogen (N) and phosphorous (P) (Chapter 1); designed and executed a field study examining sub-surface nutrient pool response to prescribed fire at a landscape-scale (Chapter 2) and conducted a controlled, simulated rainfall experiment measuring sediment yield and nutrient exports from burnt litter samples collected from three distinct Southeastern forest types (Chapter 3). The objective of these three chapters was to examine water quality variable response to burning at different spatial scales in Southeastern forests. The results of Chapter 2 suggest that prescribed fire can cause a significant pulse of N and P, but this pulse is ephemeral and likely benefits forest productivity. The experimental data collected in Chapter 3 suggests that low-to-moderate burn severity does not cause significant erosion response in Southeastern forests. However, sediment yield in runoff did significantly increase at the highest burn severity treatment in all forest types, suggesting that retained litter at low-to-moderate burn severity reduces surface runoff but also that severely burned patches can function as sediment sources throughout a landscape. Burning did not readily increase the availability of N or P in surface runoff or leachate. This thesis concludes that prescribed fire as it is practiced in forests of the Southern Appalachian Mountains, poses little risk to above and below-ground water quality.

ACKNOWLEDGMENTS

This thesis would not have been possible without the guidance, collaboration, input, mentorship, friendship and support from more people than can fit into a discrete list. However, thanks, gratitude and acknowledgement are due to many people who directly influenced the direction and success of this research. First and foremost, I would like to recognize my committee members, Dr. Patrick Hiesl, Dr. Donald Hagan and Dr. Dara Park. I cannot count the number of paper drafts I have dropped in their inboxes or the number of times I showed up at Dr. Hagan's office just to talk through ideas and ask for advice. Weekly meetings with Patrick helped keep me focused and productive. I am forever grateful for the invaluable and diligent feedback I have received from my committee throughout my Masters. I believe great things can happen when a graduate student feels genuinely valued and supported, as I have felt by my committee.

Many components of this research would not have been possible without connections and collaborations. I would like to thank Mark Hall of the South Carolina Department of Natural Resources for allowing access to the field site in Chapter 2 and for conducting the prescribed fires. Also, I need to thank Mark bailing me out when I thought I was stuck behind a forest gate on Horse Pasture Road. Dr. Billy Bridges provided invaluable help analyzing the tricky time-series data collected during Chapter 2, along with his graduate student Molly Honnecker who talked me through the analyses.

I would like to thank Walker Massey and Steven Bradley for their contribution to the accessibility and communication of this research. Walker Massey is the artist behind the

conceptual diagrams in Chapter 1, which has been accepted for publication in the Journal of Environmental Quality. Steven Bradley is a writer/photographer for Clemson University and helped share the research from Chapter 3. I would like to thank everyone who has taken an interest in these projects.

I would like to thank specific individuals that not only contributed to this thesis but also to my development as a graduate student, in no particular order. Dr. Greg Yarrow, for allowing me to assist with his wildlife management labs and attend field trips to the coast. Dr. Kyle Barrett, for our shared history at/around Sewanee and his really cool shirts. Steven Bradley, for always helping me fenagle a vehicle for field work or labs. I would also like to thank Crystal and the other technician who helped collect field data while I was traveling in summer 2019.

Dr. Wayne Chao deserves his own section in these acknowledgements. Similar to my committee members, this thesis would not have been possible without Dr. Chao's diligent support and knowledge. Dr. Chao's help was essential in operating and troubleshooting the FIAlyzer, our favorite piece of equipment. I am personally in awe of Dr. Chao's expertise in all aspects of analytic chemistry – any question I had about analyses, results, procedures, he knew it all. Whether it was determining the dilution factor for miniscule sediment samples or moving a 100-gallon tank of treated water though Lehotsky Hall, Dr. Chao was there. I know that this ease and breadth of knowledge comes with experience and I am grateful to have had the opportunity to work with Dr. Chao.

Friends, family and general supporters over the course of my master's research also deserve recognition. I would like to thank, again in no particular order, Matt Green; Helen Mohr, Calvin Norman; Megan Budnik; Lauren Diaz; Brad Wilkinson; Emily Oakman; Matt Vaughn; Simon Parker; Bethany Lefeber; Madison Lasala; Stefan Ruger and Clemson Club Swimming. Finally, none of this would have been possible without the foundation provided by my immediate and extended family, Stephen, Tristan and Nel Klimas; Misha, Kyler and Cameron Laird.

This thesis is a product of my growth as an individual, student and scientist and is dedicated to everyone undertaking their own journey.

TABLE OF CONTENTS

	Page
TITLE PAGE	i
ABSTRACT	ii
ACKNOWLEDGMENTS	iii
LIST OF TABLES	ix
LIST OF FIGURES	x
PREAMBLE	xii
INTRODUCTION	1
0.1 Justification and Aim	1
0.2 Problem Statement	2
0.3 Thesis Scope and Goal	2
0.4 Thesis Structure and Objectives	3
CHAPTER	
I. Literature Review: Prescribed Fire Effects on Water Quality in Forested Environments	6
1.1 Introduction	7
1.2 Characterizing Forested Environments Subject to Prescribed Fire	10
1.2.1 Australia	10
1.2.2 Mediterranean Europe	11
1.2.3 North America	12
1.3 Erosion, Surface Runoff and Sediment Yield After Prescribed Fire	14
1.3.1 Burn severity as an indicator of erosion	14
1.3.2 Fuel moisture and seasonality as an indicator of burn severity	20
1.3.3 Role of burn frequency on erosion response	21
1.3.4 Duration of elevated sediment yield	22
1.3.5 Erosion magnitude determined by precipitation timing	23
1.4 Prescribed Fire Effects on Water Chemistry and Macronutrients	24
1.4.1 pH	24
1.4.2 Nutrient Concentrations	25

Table of Contents (Continued)

	Page
1.4.3 Sulfate (SO_4^{2-}).....	27
1.4.4 Soluble Reactive Phosphate and Orthophosphate (PO_4^{3-})	28
1.4.5 Nitrate (NO_3^-).....	29
1.4.6 Ammonium (NH_4^+).....	33
1.5 Study Scale.....	34
1.6 Discussion.....	35
1.6.1 Prescribed fire effects on erosion.....	35
1.6.2 Prescribed fire effects on nutrient exports	36
1.7 Conclusions.....	37
II. Immediate Effects of Prescribed Fire on Sub-Surface Nutrient Pools in a Managed Yellow Pine Forest.....	40
2.1 Introduction.....	42
2.2 Methods.....	44
2.2.1 Site Description.....	44
2.2.2 Treatments.....	47
2.2.3 Sample Collection and Analysis	50
2.2.4 pH Calculation	50
2.2.5 Statistical Analysis.....	51
2.3 Results.....	52
2.3.1 NO_3^-	53
2.3.2 NH_4^+	54
2.3.3 PO_4^{3-}	56
2.3.4 pH.....	58
2.4 Discussion.....	54
2.4.1 Fire Effects on NO_3^-	59
2.4.2 Fire Effects on NH_4^+	60
2.4.3 Fire Effects on PO_4^{3-}	61
2.5 Conclusions.....	62
2.6 Study Limitations.....	63
III. Burn Severity Effects on Sediment and Nutrient Exports from Southeastern Forests using a Simulated Rainfall Experiment.....	65
3.1 Introduction.....	67
3.2 Methods.....	70
3.2.1 Sample Collection.....	70
3.2.2 Sample Treatment	71
3.2.3 Simulated Rainfall	73

Table of Contents (Continued)

	Page
3.2.4 Sediment Analysis	75
3.2.5 Sediment Digestion.....	75
3.2.6 Nutrient Analysis	75
3.2.7 Statistical Analysis.....	76
3.3 Results.....	77
3.3.1 Sediment in Runoff	77
3.3.2 Nutrient Concentrations in Runoff.....	79
3.3.3 Nutrient Concentrations in Leachate	84
3.3.4 PO ₄ ³⁻ concentrations in Sediment	85
3.4 Discussion	87
3.4.1 Sediment Yield.....	86
3.4.2 Nitrogen	88
3.4.3 Phosphorous.....	89
3.5 Conclusions.....	91
3.6 Study Limitations.....	93
IV. Conclusions.....	94
4.1 General Conclusions	94
4.2 Effects of Prescribed Fire on Sub-Surface Nutrient Pools.....	95
4.3 Effects of Burn Severity on Small Litter Samples Sediment Yield.....	97
4.4 Fire effects on Macronutrients in Runoff.....	98
4.5 Overall Conclusions.....	99
CODA	100
APPENDIX	101
REFERENCES	102

LIST OF TABLES

Table	Page
Table 1.1 A collection of studies regarding sediment exports after prescribed fire in forested environments.....	17
Table 1.2 A summary of studies concerning limiting nutrients in water systems after prescribed fire, including different forest types, season and collection method.....	31
Table 2.1 Five-month mean parameters of soil solution variable nutrient concentrations (mg/L) and pH at 30cm depth between burned and control stands in the Southern Blue Ridge mountains of upstate South Carolina.....	52
Table 3.1 Summary of soil and litter pH, total P and Total Kjeldahl nitrogen (TKN) collected from representative forest types in the Clemson Experimental Forest in Clemson, SC.....	70
Table 3.2 Description of the four burn severity and control classes used in the RFS experiment.....	71
Table 3.3 Mean Total Suspended Solids (g/L) in runoff samples and sediment yield (kg/ha) from burned litter samples (n = 4).....	77
Table 3.4 Summary of mean NH ₄ ⁺ and PO ₄ ³⁻ yield (g/ha) and concentration (mg/L) from runoff samples with standard error in parentheses.....	80
Table 3.5 Summary of mean NH ₄ ⁺ and PO ₄ ³⁻ concentration in leachate samples with standard error in parentheses	81
Table 3.6 Summary of mean PO ₄ ³⁻ concentration in sediment (mg/kg) from C, L and H burn severity treatment litter samples with standard error in parentheses	84

LIST OF FIGURES

Figure	Page
Figure 1.1 Conceptual diagram illustrating differences in constituent response to high and low-severity fire. Burn severity and the magnitude of subsequent constituent response is determined by a variety of interacting factors including fuel moisture and seasonality, but erosion response is minor in the absence of precipitation following the fire. Retained litter is effective at reducing hydrologic connectivity and reducing surface runoff	16
Figure 2.1 Weekly rainfall (mm) and temperature (Celsius) during the sampling period from February and July 2019 at Jocassee Gorges Management Area, Sunset, SC	44
Figure 2.2 Map of lysimeter transects installed February 25 th , 2019 in Jocassee Gorges Management Area, Sunset, SC (34.97972°, -82.86339°).....	46
Figure 2.3 Before (a) and after (b) the prescribed fire conducted in Jocassee Gorges Management Area, Sunset, SC on March 9 th , 2019. The b figure represents a heterogenous litter consumption pattern characteristic of a low-to-moderate-severity fire.....	47
Figure 2.4 In-ground lysimeter installed post-fire with protective cover. Fuel consumption was representative of a low severity burn and soil heating was minimal as demonstrated by the effectiveness of the metal protective cover.....	49
Figure 2.5 Soil solution NO ₃ ⁻ concentrations (mg/L) sampled from Feb. 2019 to July 2019 in a yellow pine forest in the Southern Blue Ridge Mountains of South Carolina. Values are weekly means with standard error bars	53
Figure 2.6 Soil solution NH ₄ ⁺ concentrations (mg/L) sampled from Feb. 2019 to July 2019 in a yellow pine forest in the Southern Blue Ridge Mountains of South Carolina. Values are weekly means with standard error bars.....	54

List of Figures (Continued)

Page

Figure 2.7 Soil solution PO_4^{3-} concentrations (mg/L) sampled from Feb. 2019 to July 2019 in a yellow pine forest in the Southern Blue Ridge Mountains of South Carolina. Values are weekly means with standard error bars..... 56

Figure 2.8 Soil solution pH sampled from Feb. 2019 to July 2019 in a yellow pine forest in the Southern Blue Ridge Mountains of South Carolina. Values are weekly means with standard error bars..... 58

Figure 3.1 Mixed litter samples experimentally burnt to Very Low (V), Low (L), Moderate (M) and High (H) burn severity treatment with unburn Control (C) samples 72

Figure 3.2 RFS sample mount with two Low-severity treatment Pine litter samples. Guard rails prevent runoff loss and a cover was placed over collection buckets to prevent sample saturation 73

Figure 3.3 RFS profile view diagram and dimensions (inches and centimeters) with runoff collection bucket (A), leachate collection bucket (B), mounted sample (C) and spray nozzle (D). The sample was mounted at an angle of 45° 74

Figure 3.4 Boxplot of NH_4^+ concentrations (mg/L) in runoff and leachate from pine (a), hardwood (b) and mixed (c) litter samples Control (C), Very Low, (V), Low (L), Moderate (M) and High (H) burn severity treatment 79

Figure 3.5 Boxplot of PO_4^{3-} concentrations (mg/L) in runoff and leachate from pine (a), hardwood (b) and mixed (c) litter samples at Control (C), Very Low, (V), Low (L), Moderate (M) and High (H) burn severity treatment 82

Figure 3.6 Boxplot of PO_4^{3-} yield (g/ha) from acid digested sediment samples from Pine, Hardwood and Mixed litter samples at Control (C), Low (L) and High (H) burn severity treatment 85

PREAMBLE

This thesis was an exploration. It began with a framework: prescribed fire and water quality. But what metric of water quality? How do we quantify how prescribed fire affects water quality? I dove into the literature. Numerous water quality issues associated with fire reared their heads at me – dissolved organic carbon, carcinogenic disinfectant bi-products, toxic ammonia. But I was in a forest operations lab and prescribed fire is a forest operation, which raised the question: what common environmental variables are affected by forest management practices? The answer – Sediment and nutrients.

I see the three chapters of this thesis as complementary and dynamic – the objectives, methodology and hypotheses of specific chapters evolved over the past two years as I learned and adapted. The result is a holistic examination of prescribed fires impact on water quality in the Southeast. I examined nutrient pool response to prescribed fire at a landscape-scale and quantified erosion and nutrient exports to different burn severities and forest types using a controlled experiment. This dual-scale approach strengthens the conclusions of this thesis as different aspects of the fire regime, along with environmental factors that affect water quality variables, manifest at different spatial scales. This thesis fills a contemporary gap in knowledge regarding prescribed fires impact on forest health and water quality in the Southeast.

Moreover, this Master's thesis is the culmination of two years of academic growth and personal development. My priorities in life are simple: get outside and maintain an open heart and mind. I attribute my success in graduate school to maintaining a balance of activity, work and social life. I was given a long leash to explore prescribed fire and

produce results, and I believe I have found a system that I thrive in and I believe this thesis is a testament to that. When I was younger, I did not look forward to school (though didn't we all?). The structure, the rigidity, only getting one period of environmental science a day – all made my primary education unbearable. How things have changed, because now – dare I say it – I love school. I never want to stop learning.

This thesis represents my first contribution to the body of knowledge we call science and has been one of the most formative experiences of my life. I hope the audience finds the following thesis to be comprehensive while recognizing its context in the larger field of fire ecology. We all start somewhere, and this is a beginning.

24 March 2020

Kipling Klimas

INTRODUCTION

0.1 Justification and Aim

Forests offer unique and valuable services to humans including recreation opportunities, carbon sequestration and the production of clean water. Forested watersheds are some of the most reliable sources of clean water on the planet and forests are often managed to maintain such services. At the turn of the twentieth century fire suppression initiatives were undertaken in forests across North America and Europe to prevent destructive wildfire and protect watershed resources, but policies were largely ignorant of how forests benefit from intermittent ground fires (Van Lear & Waldrop 1989). However, fire is a common and powerful disturbance in forests and fire-suppression altered natural fire regimes, causing unnatural fuel accumulation and the occurrence of destructive wildfires. In response to changing wildfire regimes and fuel dynamics, managers have adopted the use of prescribed fire in fire-adapted forests to reduce the risk and incidence of destructive wildfire, restore fire-adapted ecosystems or accomplish management objectives such as the maintenance of early successional habitat (Fernandes 2018, Nowacki & Abrams 2008). Prescribed fire is currently a powerful and effective landscape-scale management tool applied to millions of forested acres annually in North America, Europe and Australia.

0.2 Problem Statement

In nearly all cases, prescribed fire is conducted to improve forest health and maintain the valuable watershed resources forests provide to human populations, particularly fuel reduction burns to prevent large-scale wildfires. A major concern for watershed resources following wildfire is erosion and sediment deposition in perineal streams or reservoirs (Moody *et al.* 2013), as fire has immediate effects on physical, chemical and biological soil properties that make burned soils more susceptible to erosion (Cawson *et al.* 2012, Imeson *et al.* 1992). Additionally, volatilized organic matter or ash may contain biologically available forms of key macronutrients, primarily nitrogen (N) and phosphorous (P), which can be transported into lakes or streams via surface runoff. Increased nutrient concentrations in surface water, particularly P, increase the risk of eutrophication and may indicate diminished forest productivity. Destructive wildfires have been shown to denude entire forested watersheds which, in conjunction with precipitation, causes sediment or debris flows that can alter perineal drainage form, harm aquatic organism physiology or reduce reservoir capacity (Warrington *et al.* 2017). As an anthropogenic disturbance used to improve forest health, the broad aim of this thesis is to quantify erosion and nutrient movement after prescribed fire to ensure that management objectives are met without compromising forested watershed resources.

0.3 Thesis Scope and Goal

The forests of the Southeastern United States were once governed by relatively frequent, low-intensity ground fires, which created a vast mosaic of pyrogenic and mesic sites (Van

Lear & Waldrop 1989). Yet the forests of the Southeast were a victim of fire suppression in the early 20th century which, along with the loss of dominant species such as the American Chestnut (*Castanea dentata*), heralded a dramatic change in forest community composition, fuel loads and stand densities. Today, prescribed fire is applied to millions of acres annually across the Southeast to restore the structure and composition of historic fire-adapted ecological communities, prepare sites prior to seeding or maintain open understory structure. As with wildfire, prescribed fire application carries with it risks of post-fire erosion and macronutrient transport into surface water. Additionally, many watersheds in the Southern Blue Ridge mountains are ephemeral drainages and burning in high-order ephemeral watersheds can have magnifying effects on downstream constituent response (Alexander *et al.* 2007). In the Southern Blue Ridge Mountains of upstate South Carolina, where forested watersheds provide clean drinking water to both urban and rural populations, knowledge is lacking regarding the effects of prescribed fire on water quality from these forests. The goal of this thesis is to fill a gap in knowledge regarding prescribed fire effects on forest health, erosion and nutrient response in the distinct fire-adapted forests of the Southern Blue Ridge Mountains and piedmont of upstate South Carolina.

0.4 Thesis Structure and Objectives

To accomplish this goal, I first reviewed 100+ research publications, general technical reports, conference proceedings and review papers published between 1983 and 2018, regarding the effects of prescribed fire on water quality. Chapter 1 of this thesis is a

review of contemporary literature from around the world related to prescribed fire, sediment yield and macronutrient exports in which I identified the need to examine constituent response to burning at different spatial scales in the Southeast.

I conducted two studies that examined the impact of burning on water quality in Southern Appalachian forests at different spatial scales, as other studies have done to identify causal agents of post-fire erosion in different forested environments (Cawson *et al.* 2013, Johansen *et al.* 2001). Because fire effects on soil and nutrient movement are determined by a variety of interacting factors along a spatial scale that ranges from soil-pore sealing to denuding entire watersheds, this thesis includes studies conducted at the watershed-scale and using small-plot simulated rainfall to understand water quality constituent response to burning at different spatial scales in the fire-adapted forests of the Southeastern United States. Watershed-scale or hill-slope-scale studies can account for natural features of the forested landscape, such as heterogenous litter consumption or the spatial connectivity of surface runoff, in post-fire constituent recordings (Pierson *et al.* 2009). Chapter 2 of this thesis examines the response of sub-surface macronutrient pools to prescribed fire in two watersheds in an upland yellow-pine (*Pinus sp.*) forest. Small-plot or rainfall simulation studies have documented how litter combustion, intense soil heating and the development of water-repellent soil properties exacerbates erosion at the microsite-scale (Debano 2000). Chapter 3 of this thesis used a rainfall simulation experiment to assess sediment and nutrient response to burning from three different fire-adapted forests of the Southeast.

The specific objectives of this thesis are to:

- (i) Review existing literature on the effects of prescribed fire on water quality variables: sediment load and macronutrients, particularly ammonium (NH_4^+), nitrate (NO_3^-) and phosphate (PO_4^{3-}), identify knowledge gaps and suggest avenues for future research;
- (ii) Quantify the impact of prescribed fire on sub-surface macronutrient pools in a managed yellow-pine forest at the watershed scale;
- (iii) Quantify sediment and macronutrient response to burn severity treatment from small litter and soil samples from three distinct fire-adapted forest communities of the Southeast using a simulated rainfall experiment.

CHAPTER ONE: Prescribed Fire Effects on Sediment Yield and Macronutrients in
Forested Environments

A Literature Review

Abstract

This review examines the impact of prescribed fire on water quality variables (i) sediment load and (ii) limiting macronutrients in forested environments globally. The removal of insulating litter and organic matter during prescribed fire makes forest floors more susceptible to erosion and enables constituent transport into lakes and streams via surface runoff. This review aims to characterize the forested environments subject to prescribed fire; discuss factors of the fire regime that contribute to water quality concerns and offer insight into the effect of precipitation timing and study scale on constituent exports. Small scale studies examining sediment yield after prescribed fire may fail to capture the effect of landscape-scale spatial variability and watershed scale studies accounting for such variability are lacking. While small plot studies confirm that prescribed fire can alter hydrologic inputs, the ecological significance of these increases is minimal. Gaps in knowledge exist at various spatial and temporal scales and this review suggests two avenues of future research including (1) greater understanding of fire regime interactions that control surface runoff and erosion at the watershed scale and (2) monitoring forest health and ecological function after prescribed fire rather than direct nutrient inputs.

1.1 Introduction

Fire is a common disturbance in forested environments around the world, yet decades of human-induced fire suppression has altered natural fire cycles, changed understory fuel loads and increased the risk of destructive wildfire (Nowacki & Abrams 2008; Ryan *et al.* 2013). In response to changing fire dynamics, many countries have adopted the use of prescribed fire programs to mitigate the impact of large-scale wildfire in forested environments (Fernandes 2018; Neary *et al.* 1999; Van Lear & Waldrop 1989). Presently, prescribed fire is a powerful and effective tool to accomplish management objectives such as fuel reduction, ecological restoration or maintenance of timber stands (Arkle & Pilliod 2010; Knoepp & Swank 1993; Ryan, Knapp, & Varner 2013). As an anthropogenic disturbance applied to millions of forested acres annually (Melvin 2018) it is important to understand the extent to which prescribed fire accomplishes intended management goals without compromising the ability of the forest to produce clean water.

Forested ecosystems are an important source of clean water globally, and forested watersheds are often managed to provide clean water to urban populations (Hallema *et al.* 2018; Smith *et al.* 2011). The primary concern associated with fire and the ability of forests to produce clean water is elevated erosion and surface runoff post-fire, due to its ability to transport pollutants including sediment, macronutrients or other volatilized organic compounds into water systems (Anderson & Lockaby 201; Moody & Martin 2001; Smith *et al.* 2011). Although incidences of extreme post-fire erosion are normally only recorded when intense precipitation occurs shortly after the fire, fire of any severity

has immediate effects on hydrologic inputs in forested environments including vegetation mortality, insulating litter consumption and the development of hydrophobic soil properties (Moody *et al.* 2013). The magnitude of fire effects on these variables is determined the fire regime, or the characteristics of fire over time at a specific location, including burn severity, or the amount of fuel consumed, (Keeley 2009), burn patchiness (Moody *et al.* 2013), fuel moisture and seasonality (Brooks *et al.* 2004; Knapp *et al.* 2005).

Though prescribed fire is used on many landscape types, including grassland and shrubland (Harper *et al.* 2018), forested environments subject to prescribed fire are in four geographically distinct locations: Australia, southern Europe, southeastern and western North America. The geographic disparity of these forests has created unique fire regimes in terms of fuel types, seasonality and climate. Characterizing the common and unique factors that influence hydrologic response to prescribed fire is necessary to understand the potential for water quality detriment.

Wildfire effects on forest hydrology are well-documented in arid or semi-arid mountainous environments (Hallema *et al.* 2018; Moody *et al.* 2013; Moody & Martin 2001; Smith *et al.* 2011). These studies confirm that erosion and sedimentation after large-scale wildfires can have prolonged adverse effects on entire watersheds by reducing channel capacity or impairing aquatic organism physiology (Moody & Martin 2001). Information is lacking, however, regarding the effects of prescribed fire on sediment and nutrient exports in forested watersheds (Addington *et al.* 2015; Fernandes 2018; Hahn &

Coates 2018; Moody *et al.* 2013). In the 21st Century forested watersheds are becoming increasingly important sources of clean water for urban and rural populations, which makes it necessary to understand the effects of anthropogenic landscape-scale disturbance on water quality (Smith *et al.* 2011).

This review aims to synthesize the state of knowledge regarding prescribed fire effects on water quality variables (i) sediment load and (ii) limiting nutrients in forested environments along with the fire regime factors that contribute to those effects. The purpose of this synthesis is to illustrate how factors of the fire regime, including those that can be manipulated by fire managers such as seasonality and scale, affect post-fire erosion and nutrient pools in forests. To accomplish this, we reviewed and synthesized results from 23 papers, published between 1983 and 2018, that specifically concern the effects of prescribed fire on sediment and nutrient concentrations. Studies from Australia, Europe and North America were reviewed to characterize the myriad forested environments in which prescribed fire is practiced and the unique environmental factors that affect management decisions and post-fire hydrologic response. The influence of study scale, seasonality and precipitation timing on post-fire sediment and nutrient exports is discussed to offer considerations for future research and fire managers along with insight into the water quality concerns associated with increased post-fire constituents.

1.2 Characterizing Forested Environments Subject to Prescribed Fire

1.2.1 Australia

Prescribed fire in Australia is used to mitigate wildfire risk and for site preparation prior to seeding *Eucalyptus* timber plantations (Boer *et al.* 2009; Smith *et al.* 2011). Australia is home to fire adapted, evergreen sclerophyllous forests characterized by numerous species of *Eucalyptus* trees that form both closed-canopy forests and open savannahs from the tropics in the north to temperate and even alpine regions in the south (Smith & Dragovich 2008; Townsend & Douglas 2000). The climate in Australia is characterized by wet and dry seasons, with most wildfires occurring at the end of the dry season, save for coastal rainforests and temperate areas with consistent annual precipitation, (Cawson 2012; Townsend & Douglas 2000). Understory fuel reduction prescribed fires are conducted extensively in the early dry season (September-December) due to the flammable litter produced by eucalypt-dominated forests and wildfire concerns during hot, dry summers (Boer *et al.* 2009). Target environments for prescribed fire in Australia are commonly described as dry eucalypt forests that are prone to high severity wildfire that can produce extreme erosion events in their aftermath (Cawson *et al.* 2016; Smith & Dragovich 2008). These forests commonly occur at elevations under 750 meters, but sub-alpine fire-adapted eucalyptus forests occur up to 2000 meters elevation. Soils in southeastern and western Australia are characterized by igneous parent material, shallow gravely soils on slopes and peaty humus in poorly drained locations (Smith & Dragovich 2008). A high clay content makes dry-forest soils particularly susceptible to sealing, decreased infiltration and increased water repellency when exposed to direct heat at

temperatures as low as 129 degrees Celsius (Cawson *et al.* 2016). Additionally, soils are slow to form and recruit nutrients, in some cases requiring more than ten years to replenish available nitrogen (N) pools following repeated low-intensity burning (Wan *et al.* 2001).

1.2.2 Southern Europe

Forests in southern Europe have a long history of anthropogenic disturbance, including fire, that promoted the development of shrubland or open woodland (Imeson *et al.* 1992; Fernandes *et al.* 2013). Prescribed fire is primarily used to reduce fuel loads and wildfire risk, with ecological management or restoration being secondary objectives (Fernandes 2018). However, prescribed fire is still a developing management practice in the region due to public skepticism. Typical forest landscapes targeted for prescribed burning include sagebrush woodlands, Mediterranean cork oak savannahs, and plantations of native maritime pine (*Pinus pinaster* Aiton) or introduced blue gum (*Eucalyptus globulus* Labill.) (Shakesby *et al.* 1993; Marcos *et al.* 2005; Pierson *et al.* 2009; Vega *et al.* 2005). Most research done on prescribed fire and water quality is limited to *Pinus* or *Eucalyptus* timber stands in Portugal or Spain where calcareous soils are well aggregated and susceptible to pore sealing and the development of hydrophobic properties after heating (Gillon & Rap 1989; Vieira *et al.* 2015). Prescribed fire is also applied to *Quercus* spp. dominated deciduous or sclerophyllous evergreen broadleaf forests, though research on the water quality impact of these fires is lacking (Fernandes 2018). Precipitation and climate in southern Europe are variable, with some regions in the Mediterranean basin receiving as much as 1800mm of rainfall per year, and others as little as 650mm per year

(Shakesby *et al.* 1993; Marcos *et al.* 2005). Rainfall is seasonal, with most precipitation events occurring in the late spring and early summer (Marcos *et al.* 2018). Temperature variation is mild throughout the year across the entire Mediterranean basin with cool and dry winters (Imeson *et al.* 1992). Most prescribed fires in the region are conducted in the wetter spring months, contrasting traditional wildfire seasonality which usually occurs in dryer winter months (Ferreira *et al.* 2005).

1.2.3 North America

Western

Climate in western North America is difficult to characterize as the region includes some of the wettest and driest forested environments on the continent (Knapp *et al.* 2013). Fire adapted forests occur commonly in the southwest on steep slopes and are primarily evergreen and coniferous; composed of species from the genera *Abies*, *Picea*, *Pinus*, *Psuedotsuga*, *Sequoiadendron*, *Populus* and *Tsuga* (Shackelford 2010). Fire-adapted forests commonly grow on steep slopes in shallow, rocky soils (Beschta *et al.* 2004). In the semi-arid forests of the southwest wildfires historically occur in the dry season (June – August) and are commonly started by “dry” thunderstorms, where lightning ignites flammable litter (Kanpp *et al.* 2013). Mid-to-late successional forests in western North America rapidly accumulate understory fuel, leading to frequent and often severe wildfires, particularly where natural fire regimes have been suppressed (Beschta *et al.* 2004; Shackelford 2010). Northwestern coastal coniferous forests are generally too mesic for a natural fire regime and do not require prescribed fire management (Binkley 1991). But in the drier mountainous and southwestern region, prescribed fire is used to reduce

the risk of high severity wildfire, reduce understory fuel loads, curtail the spread of invasive species and to maintain succession in fire-dependent coniferous forests (Beche *et al.* 2005; Choromanska & Deluca 2001; Pollak & Kan 1998; Stephens *et al.* 2004). Intense and prolonged droughts in the western United States have created barriers to prescribed fire as fuel accumulation increases the risk of intense, high severity fire.

Southeastern

Forests in southeastern North America differ from their western counterparts in terms of species composition, climate, topography and historic wildfire regimes (Ryan *et al.* 2013). Vast woodlands of fire adapted longleaf pine (*Pinus palustris* Mill.) once spanned the southeast and many hardwood forests were adapted to regular cycles of low-intensity ground fire; it is speculated that pre-European human induced ignition played a major role in developing historic fire regimes (Nowacki & Abrams 2008). The climate is characterized by generally consistent precipitation, though further south spring and fall experience less precipitation and are generally drier due to a lack of fronts and convective storms (Ryan *et al.* 2013). More consistent precipitation and no regular, extended dry season has created a mosaic of fire adapted and mesic forest types in the southeast and midsouth regions such as southern Illinois and Arkansas, where prescribed fire is also used to manage hardwood and yellow-pine forests (Nowacki & Abrams 2008). Seasons are marked by a distinct dormant season when deciduous species lose canopy cover during the winter, though coastal evergreen forests and high elevation spruce/fir forests retain canopy cover in the dormant season. Prescribed fire in this region is commonly conducted during the drier early dormant (October – November) and late early growing

(March – May) season to restore degraded fire-adapted hardwood or yellow-pine forest communities. It is also used as site preparation method prior to plantation establishment and to maintain open, early successional habitat in timber crop stands (Elliot *et al.* 2005; Nowacki & Abrams 2008; Van Lear 1985).

1.3 Erosion, Surface Runoff and Sediment Yield After Prescribed Fire

1.3.1 Burn severity as an indicator of erosion

Fire has immediate and powerful effects on the physical structure of forests irrespective of geographic location, the most observable being vegetation mortality and litter consumption. Burn severity, or the amount of fuel consumed by the fire, is an important indicator of post-fire soil and nutrient response (Keeley 2009; Larsen *et al.* 2009). Of the studies that considered the effects of prescribed fire on sediment yield in surface runoff, many of those that reported significant findings cited high burn severity or a significant reduction in understory vegetation as the factor responsible for increased erosion (Table 1.1). High severity burns which consume a significant amount of the protective litter layer expose the underlying soils to the full heat of the fire which, at temperatures as low as 200 °C (Debano 2000), can collapse soil pore structure and reduce particle bulk density, causing the development of a water repellent, hydrophobic soil layer (Cawson *et al.* 2016; Imeson *et al.* 1992; Hubbert *et al.* 2006). However, fire-induced soil hydrophobicity is highly variable across a burnt landscape and is likely a minor contributor to post-fire erosion (Beschta *et al.* 2004). Yet homogenous litter consumption during high severity burns increases the hydrologic connectivity of the burnt landscape;

in the absence of protective litter or vegetation cover there is little to slow surface runoff velocity and the effects of fire-induced hydrophobicity may manifest (Cawson *et al.* 2013), enabling sediment transport in surface runoff (Figure 1 illustrates the effect of burn severity on erosion and sediment transport). However, fire managers target low-to-moderate severity burns that maintain heterogenous mosaic of burnt and unburnt patches. Targeting these burn severities has been shown to reduce surface runoff velocity and sediment volume inputs into water systems (Cawson *et al.* 2013).

Literature from Australia, Europe and North America reported that application of prescribed fire had a generally low impact on sediment exports from forested environments. Many of the reported impacts (Table 1.1 provides a summary of sediment exports after prescribed fire) were relatively low compared to similar studies examining sediment yield after wildfire, particularly from those examining sediment yield on the watershed scale (Smith *et al.* 2010; Townsend *et al.* 2000). In instances where prescribed fire did not have a significant effect on sediment yield authors cited low burn severity consistent with management objectives, fire exclusion from riparian zone (Smith *et al.* 2010), dilution of effects due to the size of the water system (Beche *et al.* 2005) or heterogenous litter consumption as the factors limiting post-fire surface runoff (Singh *et al.* 2017).

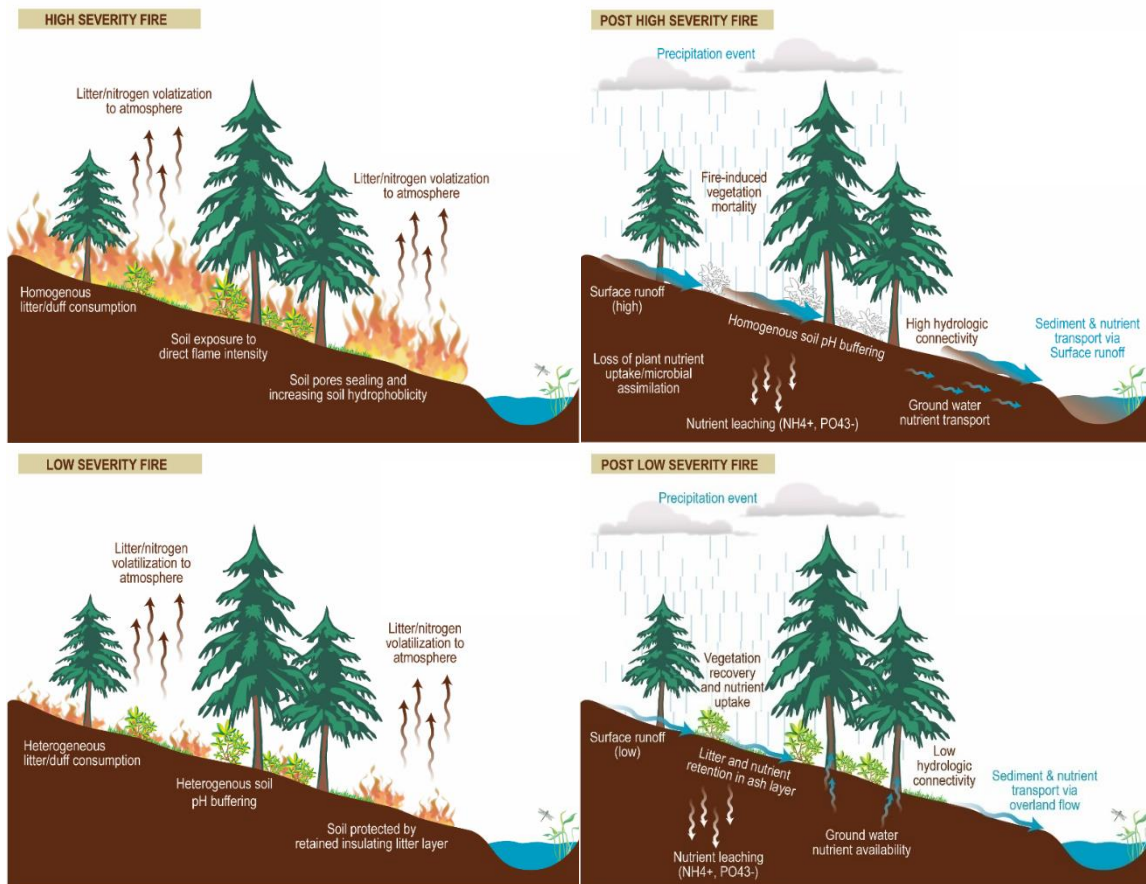


Figure 1.1: Conceptual diagram illustrating differences in constituent response to high and low-severity fire. Burn severity and the magnitude of subsequent constituent response is determined by a variety of interacting factors including fuel moisture and seasonality, but erosion response is minor in the absence of precipitation following the fire. Retained litter is effective at reducing hydrologic connectivity and reducing surface runoff.

Table 1.1. A collection of studies regarding sediment exports after prescribed fire in forested environments. Quantitative sediment export yield was based on reported values from the paper (whether cumulative, range, or arithmetic mean) and all values were standardized to kilograms per hectare (kg/ha). Note: RFS, Rainfall Simulation.

Reference	Location	Forest type	Study scale	Burn season	Sediment Export Yield (kg/ha)			Study duration	Significant change detected?	Reason for change	
					Unburn Control	Initial post-fire	Post-fire measurements				
Australia	Smith 2010	Victoria	Eucalyptus (mesic)	Catchment; 87-133 hectares	Late growing	n/a	8.717	1.875	18 months	No	n/a
	Townsend 2000	Northern Territory	Tropical woodland	Watershed; 60-1800 hectares	Late dry season	n/a	4.67	3.75	12 months	No	n/a
Europe	Fernandez 2009	Spain	Shrubland	Small plot RFS; 10x15 m ²	Early growing	n/a	248 (average)	n/a	1 month	Yes	Immediate pulse with little impact after intense application of simulated rainfall
	Gimeno-Garcia 2007	Spain	Mediterranean woodland	Hillslope transects; 4x20 m	Mid growing	85.6 (1 year cumulative)	n/a	5610 - high severity; 3260 - moderate severity (1 year cumulative)	12 months	Yes	High severity burn
	Hueso-Gonzalez 2018	Spain	Mediterranean woodland	Hillslope transects; 2x12 m	Early growing	n/a	217.2 (average); 2675.6 (maximum)	n/a	24 months	Yes	Decreases in vegetation cover in riparian zone; vegetation recovered to pre-fire levels after 7 months

Table 1.1 (Continued)

Reference	Location	Forest type	Study scale	Burn season	Sediment Export Yield (kg/ha)			Study duration	Significant change detected?	Reason for change	
					Unburn Control	Initial post-fire	Post-fire measurements				
North America	Beche 2005	California	Mixed conifer	Watershed; 26 hectares	Early dormant	n/a	n/a	n/a	n/a	No	n/a
	Benavides-Solorio 2001	Colorado	Ponderosa & lodgepole pine	Watershed; 200 hectares and small plot RFS; 1 m2	Dormant	130 (aggregate)	3420 - high severity; 760 - moderate severity (aggregate)	n/a	n/a	Yes	High severity burn
	Douglas 1983	South Carolina	Mixed pine-hardwood	Watershed; 0.48-2.12 hectares	Late growing	39.025 (average)	43.65 (average)	65.975 (average)	12 months	No	Pine beetle outbreak at study site increased flow and stream water sediment concentration in both burned and control Watersheds
	Elliot 2005	Tennessee, Georgia	Mixed hardwood	Watershed; 5-10 hectares	Late dormant	n/a	n/a	n/a	n/a	No	n/a
	Pierson 2015	Idaho	Pinyon juniper	Small plot RFS; 2x6.5 m2	Late growing	487 (average)	2676.7 (average)	448 (average)	24 months	Yes	High severity burn
	Pierson 2009	Nevada	Mixed conifer	Small plot RFS; 0.5 m2 and large plot RFS; 32.5 m2	Late growing	167 - small plot; 78 - large plot (cumulative average)	1824 - small plot; 9883 - large plot (cumulative average)	788 - small plot; 63 - large plot (cumulative average)	12 months	Yes	High severity burn, increased hydrologic connectivity
	Robichaud 1994	South Carolina	Hardwood	Watershed; 14 hectares and hillslope transects; 15x1 m	Growing	n/a	13.6 - low severity; 562.6 - high severity	n/a	n/a	Yes	Lower fuel moisture in high severity burn treatment
Shahlaee 1992	Georgia	Mixed hardwood-pine	Hillslope transects; 5x1 m	Growing	n/a	442.64 - 10% slope; 946 - 20% slope; 883.6 - 30% slope (cumulative)	n/a	8 months	Yes	20% slope sediment exports greater possibly due to less extensive root structure	

Table 1.1 (Continued)

	Reference	Location	Forest type	Study scale	Burn season	Sediment Export Yield (kg/ha)			Study duration	Significant change detected?	Reason for change
						Unburn Control	Initial post-fire	Post-fire measurements			
North America	Singh 2017	Illinois	Mixed hardwood	Watershed ; 0.07-0.12 hectares	Dormant	0.81-2.54 (range)	1.41-90.54 (range)	n/a	12 months	No	n/a
	Swift 1993	North Carolina	Mixed pine-hardwood	Watershed ; 5.25 hectares	Growing	n/a	n/a	n/a	n/a	No	n/a
	Van Lear 1985	South Carolina	Loblolly pine	Watershed ; 0.48-2.18 hectares	Late dormant	25.5	41.5	73.9	36 months	No	Harvesting after repeated low-intensity burns

1.3.2 Fuel moisture and seasonality as an indicator of burn severity

Fuel moisture is the primary factor that influences burn severity (Knapp *et al.* 2005). Low fuel moisture contributing to high fuel consumption was cited as the primary reason for high-severity burns and subsequent high sediment yield after prescribed fire (Table 1.1). Fuel moisture fluctuates by season (wet vs. dry) and at smaller time scales (daily, weekly, etc.), making it an aspect of the fire regime that managers can manipulate to target fuel consumption (Fernandes & Botelho 2003). Drier fuels are associated with higher severity burns: Knapp *et al.* (2005) suggest that greater fuel moisture during an early dry season prescribed fire was responsible for significantly lower fuel consumption than late dry season fire in adjacent watersheds. Though not statistically significant, Townsend and Douglas (2000) reported a nearly identical pattern in a tropical Australian *Eucalyptus* forest, with lower sediment exports from prescribed fires conducted in the moist early dry season. In addition to drier fuels in the late season, subsequent rainfall at the start of the wet season may cause greater erosion on higher severity burn sites where the vegetation has not had time to recover. Several studies (Benavides-Solorio *et al.* 2001; Pierson *et al.* 2015; Pierson *et al.* 2009) reported significantly greater sediment exports after prescribed fire conducted in the mid-to-late late dry season when low moisture fuels lead to higher severity burns. Timing prescribed fires during the early dry season when fuel moisture is still relatively high is an effective practice to produce low-to-moderate severity burns and allow vegetation and litter to recover before the wet season (Osborne & Kovacic 1993). Vegetation recovery and litter accumulation during the growing season insulates burned soils from the impact of intense precipitation during the wet season in forests with seasonal rainfall and can prevent high post-fire erosion events.

In southeastern North America prescribed fire is typically applied during mild weather conditions in the spring, when fuel moisture is higher which prevents extensive fuel consumption and soil heating (Addington *et al.* 2015). Late dormant or early growing season prescribed fire in the southeast lends to more heterogenous litter consumption, but the occurrence of intense storms before canopy leaf-out makes burn sites more susceptible to soil loss (Singh *et al.* 2017), though none of the studies considered from the Southeast report significantly greater sediment yield caused exclusively by seasonality (Arkle & Pilliod 2010; Cawson *et al.* 2012). Robichaud *et al.* (1994) reported significantly greater sediment exports on high severity burn plots compared to low severity during a growing season prescribed fire in South Carolina and make an important connection between fuel moisture and burn severity in that both topography (i.e. forests on cooler, north facing slopes) and seasonal drought can reduce fuel moisture, resulting in high severity burns. High fuel moisture in riparian zones may exclude fire entirely in nearly all forest environments, making riparian zones an insignificant source of sediment or nutrients in the aftermath of prescribed fire (Blake *et al.* 2009).

1.3.3 Role of burn frequency on erosion response

Many studies attribute both pulses and prolonged increases in sediment yield to prescribed fire, yet few discuss the impact of repeated burning and site history. Van Lear & Douglass (1985) recognized burn frequency in their findings and posit that the history of burning every 5 years at the study site made it more susceptible to erosion, even though no increases were recorded. Liechty & Hooper (2016) found that high frequency prescribed fire (every one-to-four years) had no impact on the productivity of a yellow pine timber stand but acknowledge lack of research on the impact of repeated burning in timber stands. Indeed, site history and burn frequency are rarely discussed in detail, though this point is only relevant for watershed scale studies where the

prescribed fire was part of an ongoing management plan and not small plot experimental fire. The studies that reported the greatest sediment yield after prescribed (Benavides-Solorio *et al.* 2001; Pierson *et al.* 2009) included only a cursory description of burn history, suggesting that the impact of repeated burning is likely minimal. Yet, to capture the effect of repeated burning on erosion and sediment loss would require extended studies over many years, or consistent monitoring of managed forests, as is already done following wildfire (Beschta *et al.* 2004).

1.3.4 Duration of elevated sediment yield

Though major sediment exports after fire occur during intense precipitation, the duration of effects in the studies considered in this review varied from immediate pulses (Fernandez *et al.* 2009) to consistently elevated sediment yield for nearly 24 months (Pierson *et al.* 2015). In instances where prescribed fire increased erosion, cumulative sediment yield during the entire study duration was quite high, being in excess of 1000 kilograms per hectare (kg/ha) in several studies (Benavides-Solorio *et al.* 2001; Hueso-Gonzalez *et al.* 2018; Pierson *et al.* 2009). While this volume of sediment was greater compared to control sampling units, it is important to note that it is common for high severity wildfire to yield cumulative sediment volumes upwards of 10,000 kg/ha for the first 2-3 years post-fire, though these accounts are primarily from semi-arid mountainous landscapes (MacDonald & Larsen 2009). The duration of elevated sediment yield was often influenced by extraneous factors including fire intrusion into the riparian zone, intense application of simulated rainfall or lack of root structure on slopes (Shahlaee *et al.* 1992). Reporting cumulative sediment over the course of a multi-month study can potentially mischaracterize the impact of sediment yield. For instance, a high erosion event during intense precipitation that releases large quantities of sediment at once is likely more detrimental to water quality than minor increases of sediment in runoff over time (Moody & Martin 2001).

Documenting examples of extreme erosion after prescribed fire, such as Cawson *et al.* (2012) did, may capture instances where sedimentation adversely affected water quality more effectively than monitoring sediment exports over time – the first precipitation event after burning is the most important for determining erosion response.

1.3.5 Erosion magnitude determined by precipitation timing

Large sediment yields following prescribed fire were contingent on either intense simulated rainfall (Pierson *et al.* 2015) or natural precipitation shortly after the fire (Hueso-Gonzales *et al.* 2018). As such, the time between fire and subsequent precipitation may be as important an indicator of erosion response as burn severity, for post-fire sediment exports are negligible in the absence of precipitation (Townsend *et al.* 2000). Furthermore, rainfall intensity plays an important role in post-fire erosion as the same rainfall intensity will produce different volumes of sediment when applied to differing burn severities; the same burn severity will produce different volumes of sediment at different rainfall intensities (Cawson *et al.* 2012). This was partially reflected in the literature, with high intensity rainfall coupled with high severity burns generated large amounts of cumulative sediment (Fernandez *et al.* 2009; Pierson *et al.* 2009). Heterogenous litter consumption following low-to-moderate-severity fire can leave microsites of retained litter that act as sediment sinks (Pierson *et al.* 2015), but during intense storms there is little difference in sediment yield between burned and unburned patches following a moderate-severity fire (MacDonald & Larsen 2009). Yet, heterogenous litter consumption in the mixed-hardwood forests of southeastern North America has been shown to enhance infiltration and reduce surface runoff velocity after precipitation, partially due to the uncommon nature of intense weather events (such as flash floods, which are more characteristic of western North America) (Singh *et al.* 2017). Townsend & Douglass (2004) make an important connection between canopy cover

retention, topography, understory recovery and sediment transport: it is largely understood, and is of practical consideration for land managers, that increased canopy cover reduces the impact of precipitation throughfall; heterogeneous burn patterns slow overland runoff velocity and regeneration of herbaceous vegetation in the growing season protects soils from erosion (Townsend & Douglass 2004). These considerations are particularly relevant for temperate, deciduous forest types where variable topography and loss of canopy cover in the dormant season can increase the effect of precipitation on fire-affected soils.

1.4 Prescribed Fire Effects on Water Chemistry and Macronutrients

1.4.1 pH

Combustion of organic elements in the litter layer and the addition of ash into water bodies following low intensity prescribed fires can affect the chemistry of nearby water systems, particularly the pH by altering relative cation ratios (Pereira 2011; Stephens *et al.* 2004; Úbeda *et al.*, 2005). Numerous studies report conflicting results on the effect of prescribed fire on water pH, indicating that different site-specific variables, such as parent material or litter composition, are often responsible for variation in stream water pH post-fire (Battle & Golladay 2003).

Monitoring post-fire changes in either terrestrial or aquatic pH is important because pH can stimulate the accumulation of certain biologically available nutrients, such as nitrate (NO_3^-) and phosphate (PO_4^{3-}) (Santin *et al.* 2018).

Many studies did not report any notable changes in pH following fire (Richter 1982; Elliot *et al.* 2005); this could be explained by abiotic buffering from local geology and relative base cation and acid anion leaching (Evans *et al.* 2017). Still other studies report both increases and decreases in pH following prescribed fire. Battle and Golladay (2003) found an insignificant pH

reduction in a depressional wetland from 4.89 (± 0.23) to 4.87 (± 0.05) following prescribed fire on longleaf pine litter, while burning wiregrass significantly increased pH from 5.49 (± 0.04) to 5.89 (± 0.02), though the ecological impact of these outcomes is likely minimal. Gu *et al.* (2008) reported an insignificant pH increase from 7.11 (± 0.09) to 7.28 (± 0.19) in wetlands following low intensity prescribed fires as a product of reduced solubilized CO₂. A significant increase in soil solution pH was reported by Pereira *et al.* (2011), with mean pH values increasing from 5.6 (± 0.35) to 7.25 (± 0.82) in an Iberian oak forest due to ash incorporation.

The effects of prescribed fire on the alkalinity or acidity of water is largely dependent on the litter composition and burn severity, with higher severity burns producing more ion-containing ash (Battle & Golladay 2003). In all cases pH changes following prescribed fire were ephemeral and water chemistry returned to baseline values within 1-2 years. Though fire can alter soil pH through the incorporation of ash and ions into the surface horizon, prescribed fire does not lead to significant or lasting alterations in water pH. However, increased pH is often beneficial to regenerating vegetation in acidic soils due to the increased availability of key macronutrients (primarily PO₄³⁻) in neutral soils (Pereira *et al.* 2011). The effects of prescribed fire on water pH are ephemeral and likely do not lead to acidification, yet other macronutrients, such as PO₄³⁻ or ammonium (NH₄⁺), become more biologically available after fire-induced pH buffering.

1.4.2 Nutrient Concentrations

Many of the papers published on soluble nutrients reported that prescribed fire had a minimal impact on stream water or soil solution concentrations (Table 1.2 provides a summary of reported findings). Of those that did report a significant increase in stream water or soil solution nutrient concentrations a majority cited high fuel consumption attributed to extraneous factors, such as unnatural nutrient saturation or dense ash deposition. Yet subsurface nutrient pools are an

important indicator of disturbance impact on an ecosystem, as loss of limiting nutrients in nutrient poor environments, such as Australian dry *Eucalyptus* forests, can impair post-fire vegetation recovery (Blake *et al.* 2009; Smith *et al.* 2010). Additionally, there is a notable lack of studies examining prescribed fire effects on nutrient exports and concentrations in forested environments outside of North America, particularly southern Europe (Table 1.2). While there is extensive research on prescribed fire effects on soil hydrophobicity in southern Europe (Ferreira *et al.* 2005; Shakesby *et al.* 1993), there is limited contemporary data on nutrient response to prescribed fire in this region.

Many of the nutrient concentration increases after prescribed fire may represent an assart effect: an ephemeral nutrient pulse following disturbance (Hahn *et al.* 2018). Whether or not these increases in nutrient concentrations constitute eutrophication and negatively impact stream ecosystems is still questionable due to the magnitude and limited duration of increased concentrations (Table 1.2). Additionally, several studies also reported reduced soil solution nutrient concentrations immediately following prescribed fire, suggesting that burning removes nutrients from a system before they can be transported into water bodies (Douglass *et al.* 1983; Elliot *et al.* 2005; Santin *et al.* 2018; Smith *et al.* 2010). As such, it is difficult to establish a causal relationship between fire induced changes to terrestrial or sub-surface nutrient pools and elevated surface water concentrations.

Another factor absent from contemporary studies is the extent to which fire impacts soil, be it homogenous or heterogenous heating. It is intuitive that low severity fire that leaves patches of unburnt litter does not have a uniform impact on forest soils, yet high severity burned patches from heterogenous burns may be significant sources of nutrients that are not characterized as such (Fenn *et al.* 2014). As such, the scale and homogeneity of soil heating and fire impacts on

sub-surface nutrient concentrations at landscape-scale is highly variable and future studies should examine the spatial extent of post-fire soil chemistry effects. The following section synthesizes specific incidences of significant nutrient increases following prescribed fire, along with the time to recovery and the environmental factors contributing to the significant increase.

1.4.3 Sulfate (SO_4^{2-})

Significant increases in SO_4^{2-} after prescribed fire were only recorded in mixed coniferous forests in California (Loupe *et al.* 2009; Stephen *et al.* 2004) though other studies conducted in other forest types (Beche *et al.* 2005; Elliot *et al.* 2005) also reported sulfate increases, albeit insignificant. SO_4^{2-} concentrations over 500 mg/L pose a health risk and may compromise municipal water clarity and aesthetic (WHO 2008). Stephens *et al.* (2004) reported a significant increase in sulfate concentrations between 0.00427 mg/L in an un-burned control plot to 0.055 mg/L in a burned plot. Loupe *et al.* (2009) reported sulfate exports increased from 19.4 mg/year pre-fire to 129.76 mg/year post-fire. Concentrations in both studies returned to baseline levels within two years. While oxidation of sulfur (S) in organic material may significantly alter SO_4^{2-} concentrations in both surface soil and surface water, even the greatest increases in these cases were likely ecologically insignificant. While SO_4^{2-} concentrations after prescribed fire do not exceed recommended drinking water standards, these studies were largely conducted in semi-arid coniferous forests; SO_4^{2-} responses in other forest types is lacking (Smith *et al.* 2011).

1.4.4 Soluble Reactive Phosphate and Phosphate (PO_4^{3-})

Soluble Reactive Phosphate (SRP) is a measure of biologically available orthophosphate (PO_4^{3-}), which is the primary nutrient limiting plant growth in aquatic ecosystems. SRP and total P were one of the most common nutrients measured among the studies sampled (Table 1.2), and while there were reported increases, numerous studies using different sampling methods reported that fire had no impact on surface water SRP concentrations. SRP increases in stream water after prescribed fire are important to document, as elevated concentrations may cause algae blooms which can affect water clarity and ultimately system productivity and function (Shackleford 2010; Stephens *et al.* 2004). Burning has been shown to temporarily increase biologically available PO_4^{3-} concentrations in in North American coniferous and Australian Eucalyptus forest soils, as sampled at the small-plot and watershed scale (Smith *et al.* 2011). Santin *et al.* (2018) suggests a process by which burning can increase the risk SRP transport into surface water even in P-limited soils: biologically available PO_4^{3-} contained in deposited ash can be transported into surface water by wind or runoff. SRP can be further transformed and biologically incorporated once it enters surface water, resulting in a net P loss from the system. However, significant SRP increases in surface water after prescribed fire are uncommon and were only occurred in longleaf pine and ponderosa pine dominated forests in Georgia and Arizona, respectively (Battle 2003; Gottfried & DeBano 1988). Battle (2003) reported significant SRP increases from pre-fire concentration of 0.00434 mg/L (4.34 ppb) to 0.0655 mg/L (65.5 ppb) post-fire. Gottfried & DeBano (1988) reported significant PO_4^{3-} increases from pre-fire concentrations of 0.46 mg/L to 0.53 mg/L post fire. Concentrations in both studies returned to baseline levels within one-year post-fire. Battle & Golladay (2003) reported that PO_4^{3-} increases in surface runoff were associated with burning vegetation, rather than fire effects on surface soils. Additionally, more

intense burning ($> 300\text{ }^{\circ}\text{C}$) of bunchgrass beneath longleaf pine conferred greater PO_4^{3-} concentrations in runoff, though this observed increase was likely ecologically insignificant due to the limited mobility of PO_4^{3-} either above or below ground.

The low-severity nature of prescribed fire in many forested environments likely does not affect P availability, as intense heating ($> 650\text{ }^{\circ}\text{C}$) is necessary to reduce organic P pools (Santin *et al.* 2018). As such, while litter combustion can increase terrestrial SRP, inorganic PO_4^{3-} exports after prescribed are unlikely to differ from unburned areas due to the inherent immobility of PO_4^{3-} and high energy needed to mobilize large quantities.

1.4.5 Nitrate (NO_3^-)

The most common source of excess NO_3^- in freshwater is surface runoff as it is highly mobile in surface water and ground water. Excess NO_3^- concentrations are a water quality concern for freshwater aquatic organisms and eutrophication in coastal waters (Alexander *et al.* 2007). From a human health perspective, NO_3^- concentrations in municipal water greater than 10 mg/L are considered unsafe for consumption and pose health concerns for infants (Binkley *et al.* 1994; EPA 2000). Organic N contained in litter is easily volatilized at temperatures as low as $200\text{ }^{\circ}\text{C}$ (Gray 2006), which can increase NO_3^- in ash and subsequent transport in surface runoff.

Additionally, increased NO_3^- concentrations in surface water after prescribed fire are likely tied to increases in pH, as nitrification is inhibited at low pH (Beche *et al.* 2005). Significant increases in NO_3^- were present in a mixed conifer and ponderosa pine forest in California and Arizona, respectively (Gottfried & DeBano 1988; Loupe *et al.* 2009). Gottfried & DeBano (1988) reported significant NO_3^- increases from 0.0002 to 0.0018 mg/L between pre and post-fire stream water concentrations. Loupe *et al.* (2009) reported a significant increase in NO_3^- exports from

4.35 mg/ha/year to 6.43 mg/ha/year between pre and post-fire rates, though the ecological significance of these increases is reportedly minimal (Table 1.2).

Table 1.2. A summary of studies concerning limiting nutrients in water systems after prescribed fire, including different forest types, season and collection method. Note: NH₄⁺ (ammonium), NO₃⁻ (nitrate), TKN (Total Kjeldahl Nitrogen), PO₄⁻ (phosphate), SRP (Soluble Reactive Phosphorous), total P (total phosphorous), Ca (calcium), K (potassium), Na (sodium), Mg (magnesium), DOC (dissolved organic carbon).

Reference	Location	Forest Type	Burn season	Nutrients measured	Sample collection method	Significant change detected?	Variables changed	Reason for change
Battle 2003	Georgia, USA	Longleaf pine	Late dormant	DOC, pH, alkalinity, NH ₄ ⁺ , SRP	Surface water sampling	Yes	NH ₄ ⁺ , SRP	Carbonates and hydroxides leaching from ash on burnt upland sites, change caused by fire effects on soil rather than vegetation
Beche 2005	California, USA	Mixed conifer	Late growing	SO ₄ ⁻ , total P, Ca, Mg, NO ₃ ⁻ , NH ₄ ⁺ , TKN	Instream	Yes	NO ₃ ⁻ , TKN, total P	Ash deposition increased available base cation ratios in soils during the first month post-fire
Douglass 1983	South Carolina, USA	Mixed hardwood	Late dormant	NO ₃ ⁻ , NH ₄ ⁺ , PO ₄ ⁻ , Ca, Mg, K, Na	Instream	Yes	Na, PO ₄ ⁻	Na and PO ₄ ⁻ exports were not affected by burn treatments and increases were only recorded prior burning and attributed to extraneous factors (pine beetle outbreak; field mouse nesting)
Elliot 2005	Georgia, USA	Mixed hardwood-pine	Late dormant	pH, NO ₃ ⁻ , NH ₄ ⁺ , PO ₄ ⁻ , SO ₄ ⁻ , Ca, Mg, K	Instream, lysimeter soil solution	No	n/a	n/a
Gottfried & Debano 1988	Arizona, USA	Ponderosa pine	Early dormant	NO ₃ ⁻ , NH ₄ ⁺ , PO ₄ ⁻ , SO ₄ ⁻ , Ca, Mg, K	Instream cup sampling	Yes	NH ₄ ⁺ , NO ₃ ⁻ , PO ₄ ⁻ , Mg, Ca, K	Delayed nitrification of elevated post-fire NH ₄ ⁺ during the winter lead to increases of NO ₃ ; significant changes of PO ₄ ⁻ , Mg and K on the order of a fraction of one part per million are likely ecologically inconsequential

Table 1.2 Continued

Reference	Location	Forest Type	Burn season	Nutrients measured	Sample collection method	Significant change detected?	Variables changed	Reason for change
Kaye 2009	Arizona, USA	Ponderosa pine	Early dormant	NO ₃ ⁻ , NH ₄ ⁺ , PO ₄ ⁻ , total P, TKN	Lysimeter soil solution	No	n/a	n/a
Knoepp 1993	North Carolina, USA	Mixed hardwood	Late dormant	NO ₃ ⁻ , NH ₄ ⁺	Instream, Lysimeter soil solution	No	n/a	n/a
Loupe <i>et al.</i> 2009	California, USA	Mixed conifer	Growing	NO ₃ ⁻ , NH ₄ ⁺ , PO ₄ ⁻ , SO ₄	Surface runoff collection, lysimeter soil solution	Yes	NH ₄ ⁺ , PO ₄ ⁻ , SO ₄ ⁻	Absence of fire for many years saturated the forest with organic nutrients
Smith <i>et al.</i> 2010	Victoria, Australia	Eucalyptus (mesic)	Late growing	NO ₃ ⁻ , PO ₄ ⁻ , total P, dissolved P, particulate P	Instream, fixed interval cup sampling	No	n/a	n/a
Stephens 2004	California, USA	Mixed conifer	Early dormant	pH, NO ₃ ⁻ , SRP, SO ₄ ⁻ Ca, Mg, K	Instream cup sampling	Yes	SO ₄ ⁻ , Ca, Mg	High fuel consumption near stream channel
Williams & Melack 1997	California, USA	Mixed conifer	Dormant	pH, NO ₃ ⁻ , NH ₄ ⁺ , PO ₄ ⁻ , SO ₄ ⁻ , silicon dioxide (SiO ₂), Ca, Mg, Na, Cl	Instream	Yes	NO ₃ ⁻ , SO ₄ ⁻ , Cl	A six year drought prior to application of prescribed fire saturated soils with SO ₄ ⁻ ; burning released excess base cations which increased availability of soluble nutrients
Van Lear & Douglass 1985	South Carolina, USA	Mixed hardwood-pine	Late dormant	NO ₃ ⁻ , NH ₄ ⁺ , PO ₄ ⁻ , Ca, Mg, Na, K	Instream	Yes	NH ₄ ⁺	Concentration effect of reduced flow during drought year

1.4.6 Ammonium (NH_4^+)

Ammonium (NH_4^+) is not the primary nutrient limiting aquatic ecosystem productivity, but concentrations as low as 1.9 mg/L may be harmful to aquatic organism physiology; water is considered unsuitable for human consumption at 17 mg/L (EPA 2013).

Ammonium increases in surface water after fire were associated with intense precipitation transporting NH_4^+ containing sediment or the concentrating effect of drought on terrestrial pools (Table 1.2). Significant increases in NH_4^+ were found in a mixed conifer forest, mixed hardwood-pine forest and longleaf pine forest in California, North Carolina and Georgia, respectively (Battle 2003; Knoepp *et al.* 1993; Loupe *et al.* 2009). Battle (2003) reported increases from concentrations of 0.0054 mg/L in control plots to 1.01 mg/L in burnt plots. Knoepp *et al.* (1993) reported a significant increase from 0.004 mg/L to 0.012 mg/L between pre and post-fire concentrations. Loupe *et al.* (2009) reported increases from 3.62 mg/ha/year to 21.93 mg/ha/year between pre and post-fire concentrations. All studies reported concentrations returned to baseline levels within two-years post-fire.

1.5 Study Scale

The scale and sampling method at which sediment or nutrient data were analyzed varied from watershed to small-plot rainfall simulations. An interesting trend is that smaller-scale studies seem to observe greater sediment yield after prescribed fire compared to the few studies that examined sediment yield from entire burned watersheds. Indeed, data on sediment yield from large scale prescribed fires is lacking as many of the studies considered collected runoff data from either hillslope transects or small plots (Table 1.1). It is difficult to determine the surface area that contributes to erosion processes after large scale wildfire (Moody *et al.* 2013) as the size of sediment sources and sinks can vary significantly at larger scales (Benavides-Solorio & MacDonald 2005; Moffet *et al.* 2007). A shortcoming of small plot or simulated rainfall experiments is that they may fail to include elements of topographic variation or spatial variability that occurs at a landscape level. This lack of variation may produce examples of extreme erosion uncharacteristic of stream water sediment concentrations (Pierson *et al.* 2009). At a watershed scale the mesic nature of riparian areas may exclude prescribed fire entirely and retained litter may slow surface runoff, acting as a sediment sink after precipitation (Blake *et al.* 2009). Experimental approaches at the small plot or hillslope scale are useful to understanding the magnitude of erosion but do not factor in landscape scale heterogeneity. Since prescribed fire is most often conducted at a landscape scale (i.e. several hectares) vegetation retention and unburned microsites make stream water sediment load from burned watersheds much lower than sediment load in runoff collected from small plot studies. However, barriers to watershed-scale studies examining erosion or nutrient

effluent exist in the form of sample collection constraints and the characterization of sediment sinks and sources throughout the burnt landscape. Study scale did not play as large a role in measuring nutrient exports, as all studies considered in this review collected data *in situ* with stream or soil solution sampling. There was a notable lack of small-plot experimental data on nutrient exports and concentrations after prescribed fire. Small plot experimental data may be useful to isolate causal agents of post-fire nutrient response by eliminating confounding environmental factors.

1.6 Discussion

1.6.1 Prescribed fire effects on erosion

This review suggests that prescribed fire can significantly increase sediment yield compared to pre-fire and un-burned control yield. This is a common issue associated with other forest management practices such as road building or harvesting and many regions have guidelines in place to reduce the environmental impact of forest management (Grace 2005). While prescribed fire can increase erosion and sediment yield, these increases are ecologically negligible in many events, particularly when compared to the erosion impact of other forest management practices such as timber harvesting or road building.

Additionally, it may be useful to compare sediment yield between prescribed fire and wildfire, as prescribed fire is often conducted with the objective of preventing destructive wildfire. Indeed, Macdonald & Larsen (2009) recorded sediment yields between 5000-10,000 kg/ha for two years following a severe wildfire in mixed conifer forest in Colorado, USA, representing an 80-fold increase in sediment yield relative to unburned

or low-severity burned areas. Moody & Martin (2001) also documented the deposition of nearly 200,000 m³ of sediment after a severe wildfire, also in Colorado, USA.

Road building and timber harvesting can also cause significant erosion in forests: sediment yield after road installation in a southern hardwood forest averaged 90,000 kg/ha/year during the first year; timber harvest operations can yield upwards of 1000 kg/ha in the absence of best management practice (BMP) compliance (Grace 2005). It is also worth noting that non-point-source (NPS) sediment yielded by other large-scale land-use systems, such as industrial agriculture, can significantly alter downstream hydrology (Nicklow *et al.* 2001).

Initial sediment yield at a landscape-scale after prescribed fire ranged from negligible (no difference from control) to roughly 3000 kg/ha, with sediment yield dropping in subsequent measurements (Table 1.1). Precipitation is another factor that influences post-fire erosion response; even during intense precipitation the magnitude of soil movement after low-severity prescribed fire likely will not adversely affect surface water. This comparison provides context for prescribed fires' limited impact on sediment yield relative to wildfire and other common anthropogenic activities.

1.6.2 Prescribed fire effects on nutrient exports

Prescribed fire effects on nutrient exports are varied and nuanced, with no clear environmental indicators (Table 1.2). Yet, prescribed-fire-induced changes to terrestrial nutrient pools in many forested environments are possible due to pH buffering and ion leaching from ash, which can translate into increased surface water concentrations. These increases, though statistically significant, likely cause little environmental impact,

particularly when compared to other land-use systems or management tools such as agriculture fertilization or livestock. Phosphate concentrations and exports after prescribed fire, though significant, were low; <1 mg/L in all cases. In contrast, agricultural land-use systems commonly yield 50-1000 g P/ha/year (Sharpley *et al.* 1992). This comparison serves to highlight the low-impact nature of prescribed fire on nutrient exports and further suggest that prescribed fire does not impair the ecological function of forested watersheds.

1.7 Conclusions

This review presents a quantitative synthesis on the effects of prescribed fire on sediment exports and soluble nutrient concentrations in forested environments globally. In general, low-severity prescribed fire is a beneficial disturbance to forest ecosystems and current research supports this. However, there are gaps in our knowledge of how factors of the fire regime interact in different forest environments at different spatial scales, making it difficult to quantify the possibility of adverse fire effects on forest health and water quality. The conclusion of this review is that prescribed fire is an effective management tool that does not have adverse effects on forest health and watershed resources by means of excess sediment or nutrient concentrations. Though sediment transport in runoff increases after prescribed fire in certain situations, these erosion events are associated with intense precipitation shortly after the fire and do not impair ecosystem function. Burn severity and subsequent soil mobility is easily controlled by managing aspects of

the fire regime such as seasonality or fuel moisture, along with natural forest characteristics, such as root mats or even fossorial insects (Blake *et al.* 2009).

Heterogenous litter retention after low-to-moderate severity prescribed fire reduces runoff velocity is effective at minimizing sediment and nutrient inputs into surface water. Future research on water quality from forested environments after prescribed fire should be broadened to include (i) better understanding of fire regime interactions at watershed and small-plot spatial scales that determine burn severity and (ii) landscape-scale documentation of post-fire erosion events and sub-surface nutrient pools. Generally, studies conducted at smaller scales documented greater sediment yield than watershed-scale studies, as smaller scale studies fail to capture the variability of forest floors at different spatial scales. When interpreting the results of erosion studies, cumulative sediment yield over time should not be conflated with sediment pulses produced by extreme precipitation. Efforts to sample sediment in perennial streams during the window of disturbance after prescribed fire may capture sediment concentrations after prescribed fire more accurately than extended observations. Additionally, greater understanding of the effect of burn frequency in a watershed is necessary as the maintenance of burned patches in a watershed may function as sediment sources.

While fire effects on sub-surface nutrient concentrations and terrestrial nutrient pools do not easily translate into increased stream water nutrient concentrations, fire-induced soil pH buffering demonstrates how fire can alter terrestrial nutrient pools. There exist several gaps in knowledge regarding fire effect on nutrients including (i) burn severity and the homogeneity of fire-induced soil pH buffering, (ii) interaction between burn severity and

the leaching of cations and anions and (iii) how the combustion of different fuels from different forest types contributes to constituent inputs. Additionally, there is a significant gap in research on constituent exports from some forest types, such as southern European hardwood forests (Fernandes 2018). Monitoring forest health and ecological function (i.e. nutrient cycling processes) may be better indicator of prescribed fire impact on watershed resources rather than stream or lake water constituent concentrations, which are usually rapidly diluted.

CHAPTER TWO: Immediate Effects of Prescribed Fire on Sub-Surface Nutrient Pools in
a Managed Yellow Pine Forest

A Field Study Conducted Spring 2019

Abstract

Prescribed fire is a forest management tool applied to millions of acres across the southeastern United States annually, yet little is known about how prescribed fire influences soil properties in the region. Sub-surface pools of nitrogen (N) and phosphorous (P) are important indicators of ecosystem response to disturbance and are likely modified – at least temporarily – by fire. The goal of this study was to determine if prescribed fire impacts pools of key macronutrients, primarily ammonium (NH_4^+), nitrate (NO_3^-) and orthophosphate (PO_4^{3-}) as well as pH. To accomplish this, we undertook a 5-month study monitoring sub-surface nutrient concentrations before and after prescribed fire in a managed yellow pine (*Pinus sp.*) stand in the Southern Blue Ridge Mountains of South Carolina. Soil solution was collected weekly from 30cm porous cup suction lysimeters between February and July 2019. We compared the mean, maximums and predicted Gaussian peak values of the nutrient concentrations and pH to quantify the immediate effects of prescribed fire. Soil solution pH and NO_3^- parameters were unaffected by prescribed fire application. Prescribed fire caused a significant increase in the maximum NH_4^+ and PO_4^{3-} concentrations. Post-fire NH_4^+ concentrations reached a maximum of 18.0 mg/L before declining two weeks post-fire. PO_4^{3-} concentrations in burned stands reached a maximum of 6.57 mg/L and remained elevated for four weeks

post-fire however leaching was minimal due to complexation to soil metal cations. The PO_4^{3-} and NH_4^+ increases observed in this study are unlikely to impair water quality, due to their low concentrations and ephemeral nature, and the observed NH_4^+ increases may be beneficial to post-fire vegetation recovery.

2.1 Introduction

Prescribed fire is applied to over 2 million forested acres annually in the Southeastern United States (Hallema *et al.* 2018, Melvin 2018). Prescribed fire is a valuable management tool in numerous forested environments and is understood to benefit the long-term functions of fire-adapted ecological communities (Certini 2005, Nowacki & Abrams 2008). Yet contemporary knowledge on the immediate effects of prescribed fire on forest health and nutrient cycling in managed timber crop stands remains limited in the Southeast, where it is practiced extensively to meet productivity and forest health objectives (Elliot & Vose 2005, Melvin 2018, Van Lear *et al.* 1989).

Application of low-severity prescribed fire has immediate effects on the biological, physical and chemical properties of soil, which affect the movement and concentrations of limiting macronutrients, primarily available forms of nitrogen (N) and phosphorous (P) (Fenn *et al.* 2014, Richter *et al.* 1982, Schoch & Binkley 1986). Typically, the combustion of woody debris or leafy organic matter results in the rapid loss of N and P containing biomass from the forest floor by means of volatilization, ash transportation and/or mineralization (Iechty & Hooper 2016, Knoepp *et al.* 2009, Knoepp & Swank 1993). However, biologically available forms of inorganic N or P may persist post-fire in the absence plant re-uptake. Movement of excess quantities of these nutrients into perennial lakes or streams raises water quality concerns for both aquatic life and human health (Hallema *et al.* 2018, Son *et al.* 2015). Additionally, loss of N from a system may impair post-fire recovery and can be indicative of diminished site productivity (Djordjic *et*

al. 2004, Richter *et al.* 1982). Studies suggest that low-severity fire has minimal long-term impact on forest nutrient pools and site productivity (Knoepp *et al.* 2009), yet knowledge on immediate nutrient pool responses to prescribed fire is lacking.

Prescribed fire is used to maintain early successional habitat in yellow pine (*Pinus sp.*) stands in the Southern Blue Ridge Mountains by the South Carolina Department of Natural Resources (SCDNR). The practice is largely effective at curtailing the growth of competitive woody species, primarily mountain laurel (*Kalmia latifolia* L.), red maple (*Acer rubrum* L.) and tulip poplar (*Liriodendron tulipifera* L.) as well herbaceous species such as greenbrier (*Smilax sp.*) and blackberry (*Rubus sp.*). While measures are taken to limit the extent and intensity of the prescribed fire, contemporary knowledge is limited on the immediate impact of prescribed fire on water quality from watersheds in managed timber stands. It is important to assess the impact of prescribed fire on small forested watersheds due to the magnifying effect of high order streams on downstream water quality (Alexander *et al.* 2007). Regulating agencies have established concentration standards in surface waters to protect both aquatic organisms and human health to protect the value of forested watersheds as sources of clean water (EPA 2013, Hallem *et al.* 2018). The goal of this study was to quantify immediate sub-surface N and P response to prescribed fire to identify possible water quality or site productivity risks. To accomplish this, we initiated a 5-month study monitoring available sub-surface inorganic N and P concentrations, specifically ammonium (NH_4^+), nitrate (NO_3^-) and orthophosphate (PO_4^{3-}) as well as pH. The specific objectives were to (1) quantify the immediate effect of prescribed fire on sub-surface concentrations of available NH_4^+ , NO_3^- and PO_4^{3-} and (2)

determine if prescribed fire has the potential to negatively affect water quality or forest health through the leaching of key macronutrients.

2.2 Methods

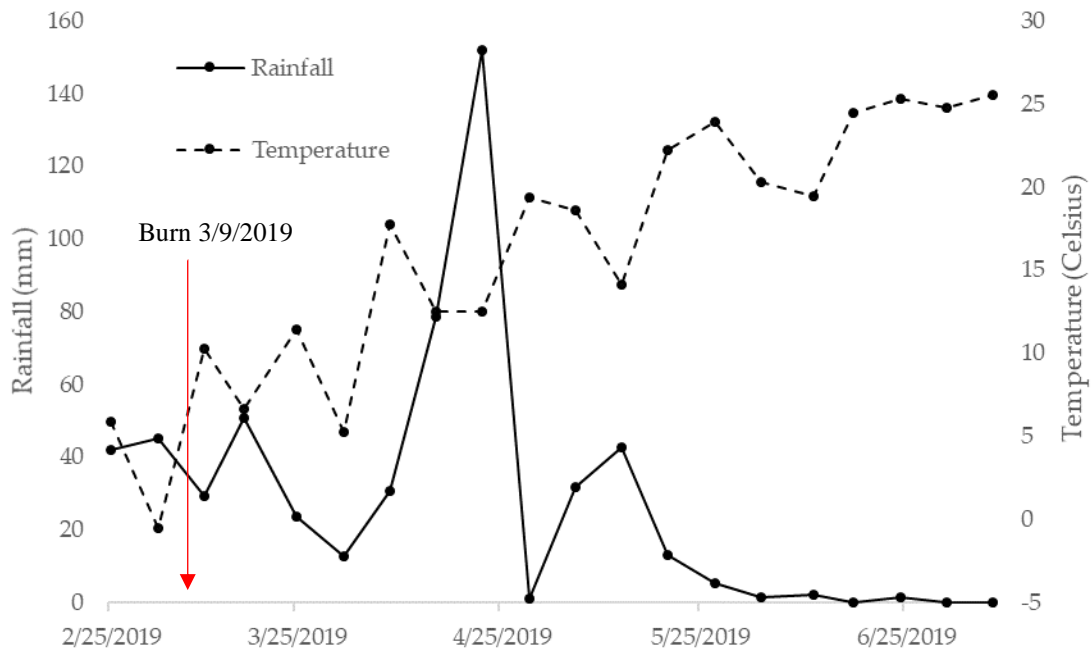


Figure 2.1: Weekly rainfall (mm) and temperature (Celsius) during the sampling period from February and July 2019 at Jocassee Gorges Management Area, Sunset, SC.

2.2.1 Site Description

The Jocassee Gorges Management Area is located at the convergence of the Piedmont foothills and the lower Blue Ridge Escarpment in the upstate of South Carolina. The landscape contains sharp contrasts as the foothills of the Piedmont rise nearly 2,000 vertical feet marking the rise of the southern Blue Ridge Mountains. The topography is governed by steep gorges incised into the metamorphic parent material and

slopes are covered by a mixed hardwood-conifer overstory. Dominant canopy species include yellow pines (*Pinus virginiana* Mill., *P. pungens* Lamb., *P. echinata* Mill.), white oak (*Quercus alba* L.), *L. tulipifera*, *A. rubrum*. Soils were Pacolet series (PaC2) histosols, characterized by a porous, fine sandy loam A horizon and a pronounced sandy clay B horizon. Soils at the site were relatively acidic (Table 2.1) and had low total N, which is characteristic of yellow pine forests. The lower Blue Ridge Escarpment has an average annual rainfall of 2000 mm (Sunset, SC, National Climatic Database: www.ncdc.noaa.gov), though mean weekly rainfall during the study period was 28.9 mm. Temperatures ranged between 0 and 26 degrees Celsius during the study period from February to July, which is representative of historic seasonal climate (Figure 2.1). The study site had been previously burned in March 2015.

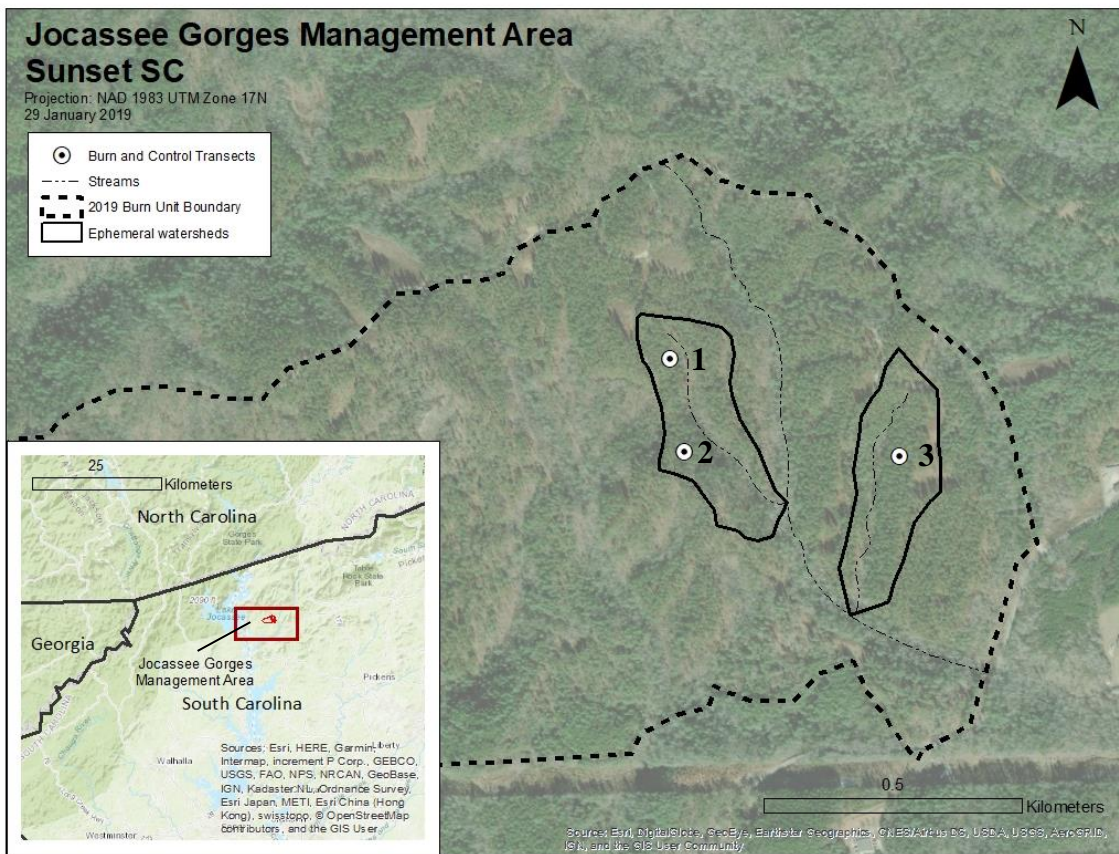
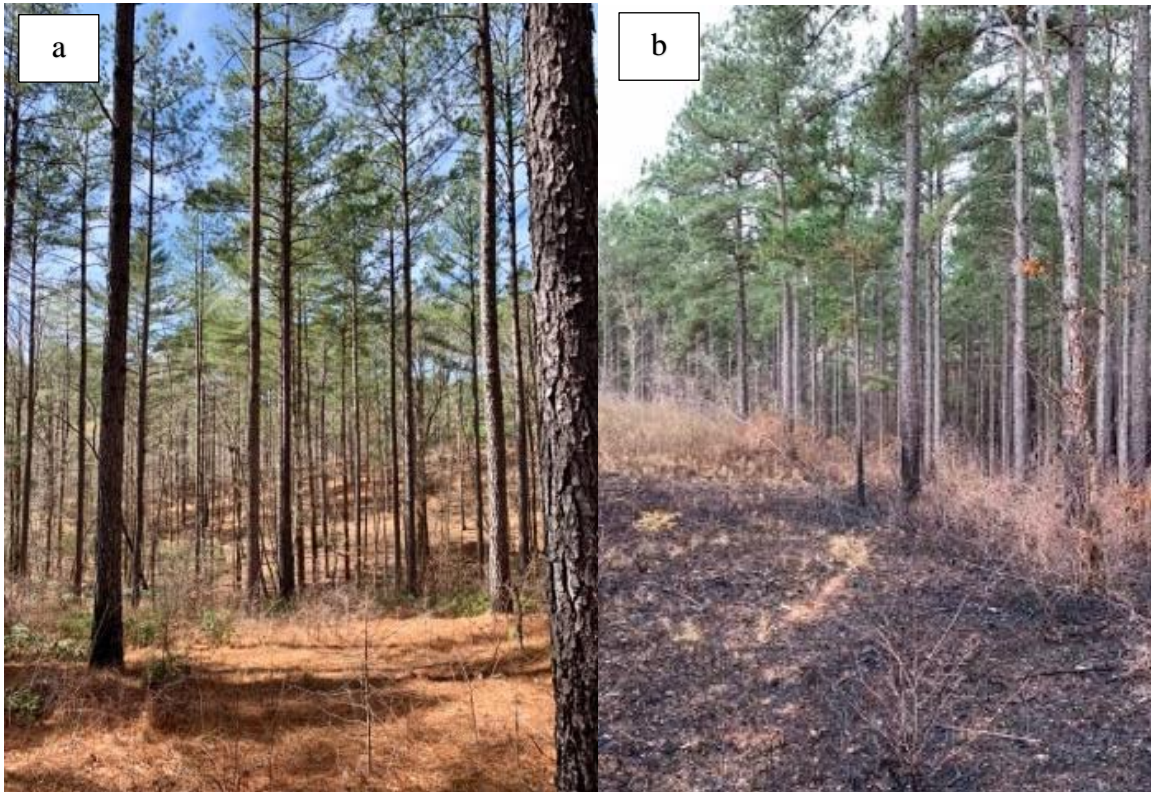


Figure 2.2: Map of ephemeral watersheds and lysimeter sampling sites installed February 25th, 2019 in Jocassee Gorges Management Area, Sunset, SC (34.97972°, -82.86339°). Site numbers are: 1, Control; 2, Burn; 3, Burn.



2.2.2 Treatments

Figure 2.3: Before (a) and after (b) the prescribed fire conducted in Jocassee Gorges Management Area, Sunset, SC on March 9th, 2019. The after figure represents a heterogenous litter consumption pattern characteristic of a low-to-moderate-severity fire.

The SCDNR conducted a prescribed fire a yellow pine timber stand in the Jocassee Gorges Management Area on March 9th, 2019. Prior to burning (late February 2019) soil solution sampling transects were established in two ephemeral watersheds (Figure 2.2). Sampling transects were installed on the hillslope and were comprised of upslope (Top) and downslope (Bottom) sampling points 30 meters apart. A total of 20 lysimeters were installed in 10 transects with five transects in two ephemeral watersheds that emptied into the same perennial drainage. Two transects in each stand were designated as un-burned controls. The prescribed fire was low severity with charred litter retention and patches of

un-burned litter in gullies or on shaded slopes. Ignition pattern and mesic litter in gullies excluded fire from the riparian buffer zone surrounding the main perennial drainage.



Figure 2.4: In-ground lysimeter installed post-fire with protective cover. Fuel consumption was representative of a low severity burn and soil heating was minimal as demonstrated by the effectiveness of the metal protective cover.

2.2.3 Sample Collection and Analysis

We collected weekly soil solution samples from 30 cm porous cup suction lysimeters (Hanna Instruments HI89300-30) starting February 2019 (approximately 2 weeks before the prescribed fires) and continued sampling through July 2019 (4 months following prescribed fire application). Soil solution was collected at the intersection of the A/B soil horizons approximately 30 cm below the surface. A total of 185 samples were collected over the course of the study, with 10-15 samples collected every week from 18 lysimeters. Lack of solution in 12 lysimeters was attributed to low precipitation and ground water uptake by regenerating plants starting in May 2019 (Figure 2.1).

Ammonium concentrations were measured using the Environmental Protection Agency (EPA) recommended FIA-012 method. Nitrate concentrations were also measured using the EPA compliant FIA-026 Cadmium reduction method (EPA 353.2, SM 4500-NO₃). Phosphate concentrations were measured using the EPA compliant FIA-073 sequential flow injection method (EPA 365.1). Sample pH was measured using a Hanna Instruments HI9814 probe.

2.2.4 pH Calculation

pH data was corrected due to contamination from bleach used to sterilize lysimeters prior to installation. In order to correct pH readings, we re-sterilized three lysimeters with Hanna Instruments bleach cleaning solution (HI83900) that was included with the lysimeter purchase. We sampled distilled water (pH = 7.0) 18 times (once for each week of data collection) and recorded the difference between the known and contaminated pH.

This difference was used to adjust pH measurements from lysimeters to account for the contamination from residual bleach in the ceramic cap.

2.2.5 Statistical Analysis

We used a control-impact experimental design to compare nutrient concentrations and pH between control and burned transects. There was no effect of lysimeter sampling point (Top/Bottom) on nutrient concentration or pH so data from burned and un-burned treatments were pooled by transect to compare nutrient concentrations and pH. We examined the parameters of mean, maximum and predicted Gaussian peak to compare average soil solution concentrations between control and burned transects across the 5-month duration of the study with transect as the unit of analysis. A specialized non-linear model was used to estimate Gaussian peak values by transect. Comparisons were conducted by analysis of variance (ANOVA) and summary tables for each parameter by transect and condition (control vs. burn) over the 5-month sampling period were generated in JMP (JMP Pro, Version 14.1.0. SAS Institute Inc., Cary, NC, 1989-2020). We conducted repeated measures ANOVA on pooled weekly values to determine significant differences between control and burned soil solution nutrient concentrations and pH during each sampling event.

2.3 Results

The prescribed fires in this study resulted in low-severity burns, consistent with management goals (Figure 2.3). The litter layer was partially consumed but the underlying duff layer experienced minimal charring, with little bare soil was exposed. Soil heating was likely minimal as an intact duff layer is an effective insulator. Litter was retained in gully bottoms and burning was minimal on shaded slopes. Post-fire grass and forb regeneration was rapid in burned stands at the onset of the growing season in May 2019.

Table 2.1: Five-month mean parameters of soil solution variable nutrient concentrations (mg/L) and pH at 30cm depth between burned and control stands in the Southern Blue Ridge mountains of upstate South Carolina. Values marked by an asterisk are significantly different from the control at the 0.05 level. Parenthetical values are standard deviation.

Parameter	Condition	PO ₄ ³⁻	NO ₃ ⁻	NH ₄ ⁺	pH
Maximum	Control	1.90 (4.0)	0.49 (0.33)	1.37 (1.0)	5.7 (0.07)
	Burn	6.57 (0.2)*	0.65 (0.36)	18.02 (11.03)*	6.1 (0.3)
Range	Control	1.88 (0.04)	0.482 (1.0)	1.36 (1.0)	2.6 (0.3)
	Burn	6.29 (3.5)*	0.64 (0.33)	17.94 (11.0)*	2.53 (0.6)
Predicted Peak	Control	3.54 (2.14)	0.84 (0.21)	0.36 (0.20)	4.6 (0.1)
	Burn	4.27 (2.41)	0.78 (0.68)	54.88 (94.03)	8.9 (5.8)
Mean	Control	0.53 (0.04)	0.1 (0.04)	0.21 (0.1)	4.3 (0.01)
	Burn	1.55 (1.43)	0.15 (0.07)	2.48 (2.2)	4.9 (0.01)*

2.3.1 NO_3^-

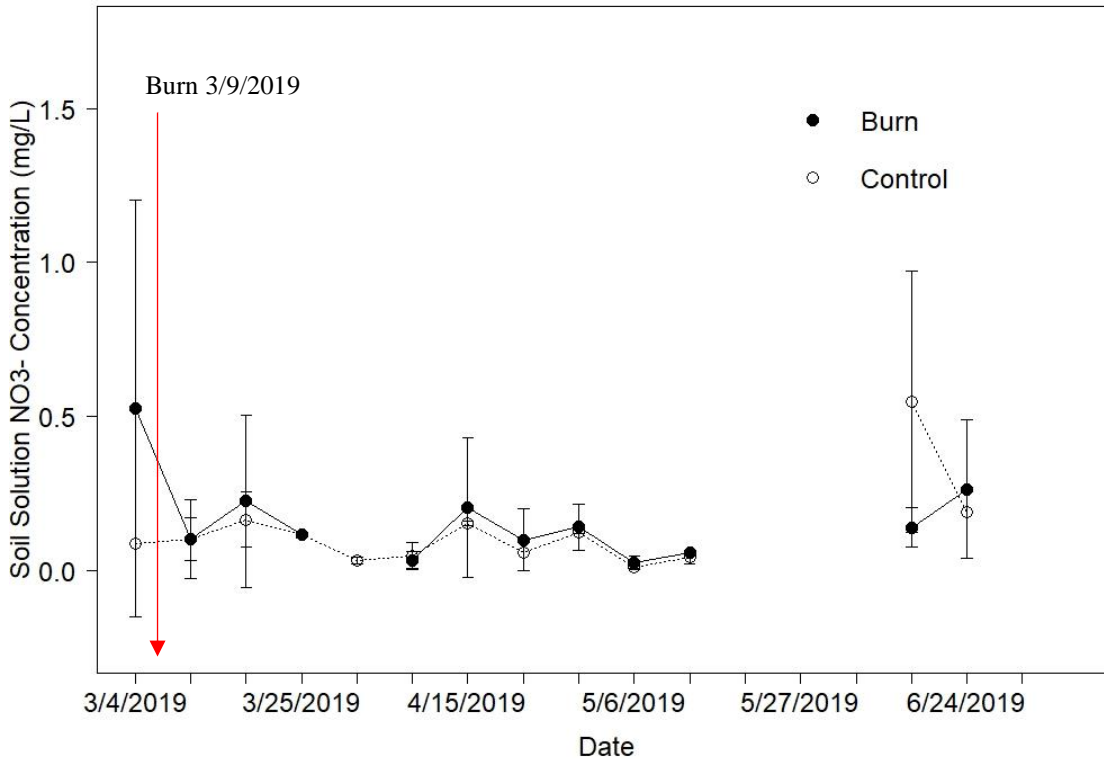


Figure 2.5: Soil solution NO_3^- concentrations (mg/L) sampled from Feb. 2019 to July 2019 in a yellow pine forest in the Southern Blue Ridge Mountains of South Carolina. Values are weekly means with standard error bars.

NO_3^- concentrations were low throughout the entire sampling period, reaching maximum concentrations of $0.65 (\pm 0.4)$ mg/L with no difference in the range of concentrations between burned and control transects ($p = 0.87$). Additionally, the maximum ($p = 0.81$), predicted Gaussian peaks ($p = 0.86$) and mean ($p = 0.87$) were not different between burned and control transects (Table 2.1). Gaps in recorded measurements (Figure 2.5) represent concentrations below the detection threshold of the FIAlyzer of 0.005 mg/L.

2.3.2 NH_4^+

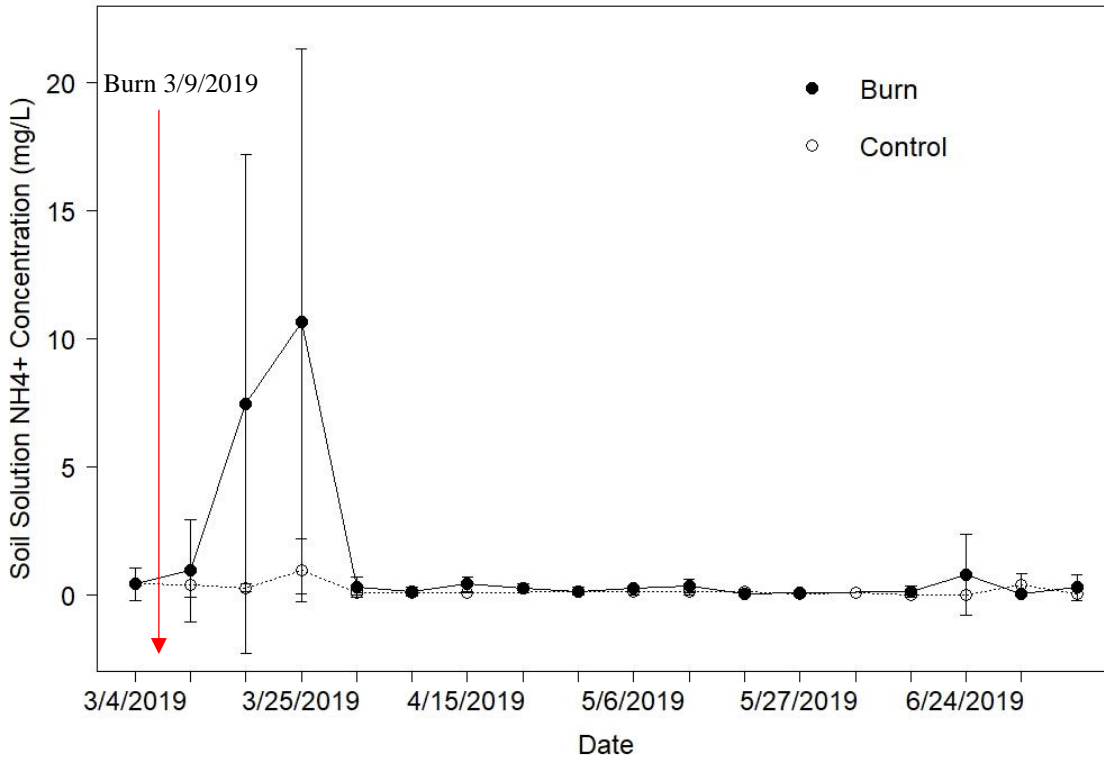


Figure 2.6: Soil solution NH_4^+ concentrations (mg/L) sampled from Feb. 2019 to July 2019 in a yellow pine forest in the Southern Blue Ridge Mountains of South Carolina. Values are weekly means with standard error bars.

Prescribed fire caused a significant increase in the range ($p = 0.0153$) and maximum ($p = 0.0136$) of NH_4^+ concentrations at 30 cm depth compared to unburned control (Table 2.1). Concentrations in burned transects dropped to close to control values (<0.1 mg/L) approximately three weeks post-fire (Figure 2.6). It is also important to note that the predicted peak NH_4^+ concentration of $54.88 (\pm 94.03)$ mg/L was nearly five times greater than the surface water toxicity threshold for aquatic organisms of 5-10 mg/L (EPA 2013).

However, this predicted peak value was not different from the control due to high variance ($p = 0.23$).

2.3.3 PO_4^{3-}

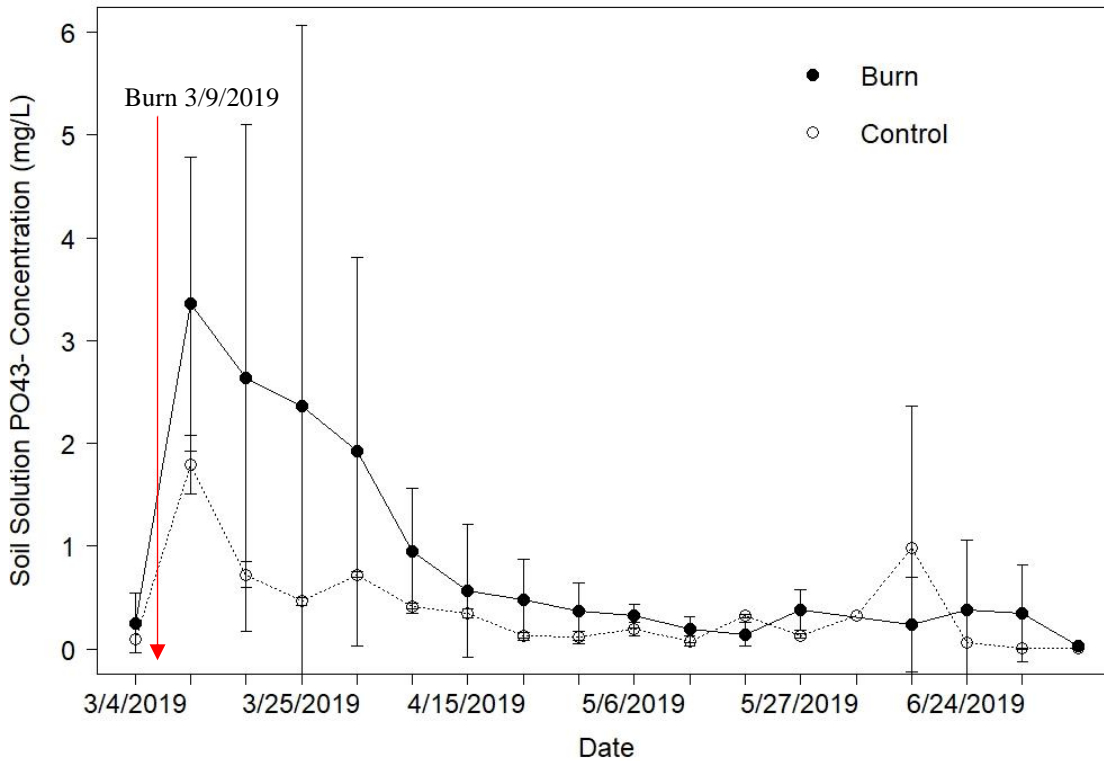


Figure 2.7: Soil solution PO_4^{3-} concentrations (mg/L) sampled from Feb. 2019 to July 2019 in a yellow pine forest in the Southern Blue Ridge Mountains of South Carolina. Values are weekly means with standard error bars.

Prescribed fire increased available inorganic PO_4^{3-} concentrations at 30cm depth. The range ($p = 0.0428$) and maximums ($p = 0.0203$) were significantly greater in burn transects than control (Table 2.1). Predicted peak concentration was not different between burn and control transects ($p = 0.819$). The maximum PO_4^{3-} concentration of $6.57 (\pm 0.2)$ mg/L was recorded during the second week of sampling post-fire (Figure 2.7). Elevated PO_4^{3-} concentrations (>1.0 mg/L) were measured for five weeks post-fire and did not experience a notable return to baseline concentrations as documented for NH_4^+ , though

there were low (<0.1 mg/L) concentrations recorded in burned samples throughout the sampling period (Figure 2.7).

2.3.4 pH

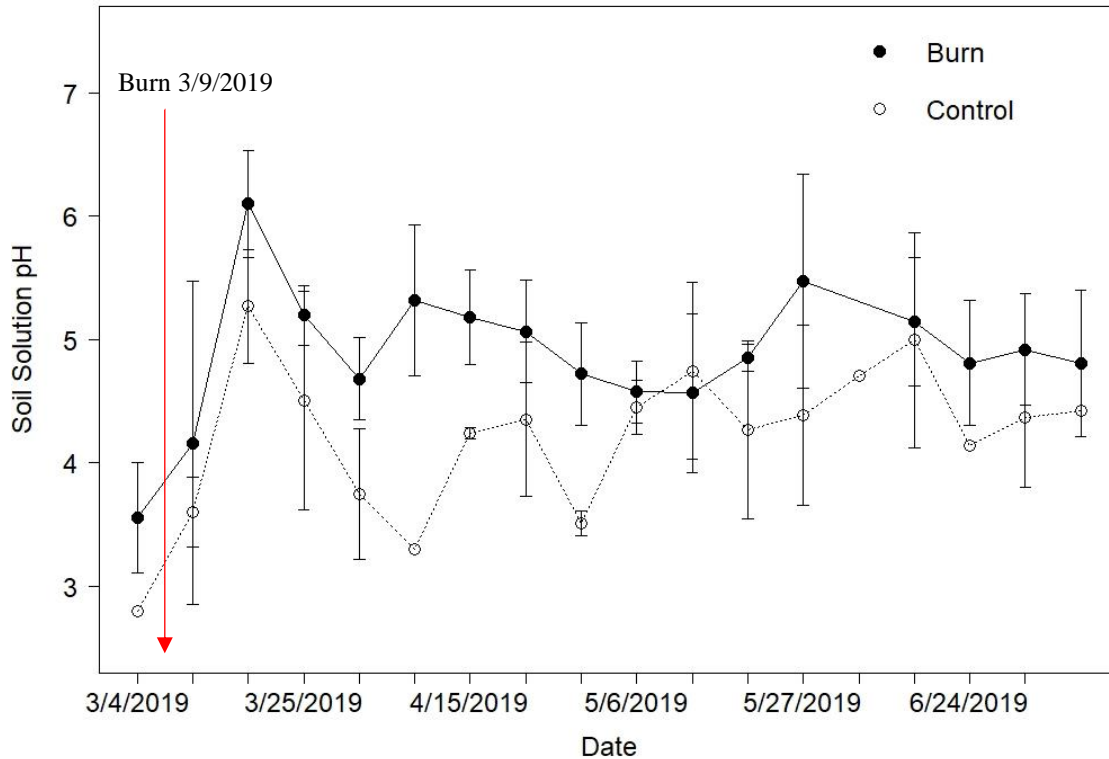


Figure 2.8: Soil solution pH sampled from Feb. 2019 to July 2019 in a yellow pine forest in the Southern Blue Ridge Mountains of South Carolina. Values are weekly means with standard error bars.

Mean 5-month soil solution pH was greater in burn (4.9 ± 0.01) than control (4.3 ± 0.01) transects ($p = 0.0028$); solution pH max, range and predicted peak were unaffected by burn treatment. The predicted Gaussian peak (8.9 ± 5.8) and the observed maximum (6.1 ± 0.3) in burned transects suggests some fire-induced pH buffering, though these parameters were not statistically different from the control. There were no discernible trends in burn and control solution pH over the 5-month sampling period, save generally lower pH in control transects (Figure 2.8). 5-month mean soil solution pH in both burn and control transects was representative of local soil pH indicating that, although mean

pH was elevated in burn transects, prescribed fire impacts on pH buffering were limited and heterogenous across the landscape.

2.4 Discussion

2.4.1 Fire Effects on NO_3^-

Increased terrestrial or subsurface NO_3^- concentrations after fire is unlikely due to the low temperature at which NO_3^- is volatilized (Certini 2005, Knoepp & Swank 1993). The data suggest that prescribed fire had little impact on sub-surface NO_3^- concentrations. Yet an important inference is that prescribed fire did not cause a significant loss of N from the forest ecosystem: had a significant *decrease* in NO_3^- concentration been detected as a result of burn treatment it may indicate a substantial loss of both organic and inorganic N from the system (Vose *et al.* 2005). However, post-fire N loss by volatilization or plant uptake may benefit forests by reducing nutrient pools that have become N-enriched in the absence of fire. Additionally, N response to fire is strongly associated with soil heating; low-severity fuel consumption, low soil heating and low total N in both litter and soil are the primary factors explaining the lack NO_3^- response in this study (Knoepp & Swank 1993, Richter *et al.* 1982). Though NO_3^- concentrations were low (<0.1 mg/L) and at times below the detection threshold, they were representative of ambient concentrations in undisturbed, small forested watersheds of between 0.05-0.15 mg/L (Binkley *et al.* 2004).

2.4.2 Fire Effects on NH_4^+

This study documented a pulse of NH_4^+ immediately following the application of low-severity prescribed fire. The observed NH_4^+ increase echoes the results of similar studies that also reported increased NH_4^+ in stream water or soil solution after burning (Clinton *et al.* 2003, Knoepp *et al.* 2009, Schoch & Binkley 1986). A likely explanation for this increase is that volatilized N contained in the ash layer leached downward, allowing NH_4^+ to pool in the soil until it was either absorbed by plants, adsorbed to negatively charged clay particles or transformed into NO_3^- (Certini 2005, Debano 2000, Knoepp & Swank 1993). The decline of NH_4^+ in burn transects to near control values (<0.2 mg/L) between the third and fourth week of sampling (March 25th – April 1st, 2019) suggests that rapid nitrification and mineralization of available NH_4^+ occurred at the start of the growing season (Knoepp & Swank 1993, Weil & Brady 2017). However, the rapid NH_4^+ decrease observed in this study contrasts similar studies that reported extended periods of elevated NH_4^+ in stream water or soil solution, though at concentrations on the order of <0.1 mg/L (Knoepp & Swank 2005, Vose *et al.* 2005). High clay content at the intersection of the A/B soil horizon in southern Appalachian soils prevents NH_4^+ leaching, and elevated NH_4^+ pools can function as a source for both plant uptake and conversion to NO_3^- (Knoepp & Swank 2005). This study was unable to establish a causal relationship between increased NH_4^+ concentrations and NO_3^- concentrations, suggesting that mobilized NO_3^- was readily absorbed by plants. Fire seasonality may explain extended periods of elevated NH_4^+ in other studies: fire-induced changes to inorganic N persisted in the absence of plant

regeneration or microbial activity at the start of the dormant season (Knoepp & Swank 2005).

Though the 5-month mean NH_4^+ concentration of 2.48 (± 2.2) mg/L from burned transects was not significantly different from control transects ($p > 0.1$), it is greater than flow-weighted ambient concentrations in undisturbed southeastern streams of approximately 0.05 mg/L (Binkley *et al.* 2004). While inorganic NH_4^+ experienced a pulse following prescribed fire application, total N pools were likely depleted by means of volatilization or conversion to inorganic forms (Weil & Brady 2017, Fenn *et al.* 2014). In an N-limited forest ecosystem, loss of organic N pools may initially reduce site productivity, yet from a restoration and water quality perspective, intermittent burning likely prevents sub-surface N saturation and any subsequent movement into surface water. The drop of NH_4^+ concentrations further suggests that the observed pulse was representative of an Assart effect, or a pulse of nutrients after disturbance (Hahn *et al.* 2018). Regenerating herbaceous vegetation and grasses were likely responsible for the rapid decline in soil solution NH_4^+ rather than by yellow pines. The prescribed fire, in this instance, likely confers an advantage to the fire-adapted yellow pine overstory whereby the vegetation mortality and total N pool reduction limits the growth of competitive hardwood or shade tolerant species.

2.4.3 Fire Effects on PO_4^{3-}

Few studies have examined the effects of prescribed fire on sub-surface or inorganic P and those that have reported minimal response to burning (Binkley *et al.* 2004, Elliot *et al.* 2005). In contrast, this study documented a slight PO_4^{3-} increase after prescribed fire. This represents perhaps the greatest concern for water quality associated with prescribed fire, as the 5-month average concentration (1.55 ± 1.43 mg/L) from burn transects was many times greater than PO_4^{3-} concentrations in undisturbed southeastern streams of approximately 0.014 mg/L (Binkley *et al.* 2004). The gradual decline of PO_4^{3-} concentrations in burned transects coincides with soil pH decline (Figure 2.7), making complexation onto soil metal cations (i.e. aluminum) and re-incorporation into organic sub-surface pools a likely sink. While prescribed fire caused a pulse of PO_4^{3-} , P loss and leaching was minimal due to low precipitation, soil water uptake from plant regeneration and complexation to metal cations as soil pH fluctuated. Elevated PO_4^{3-} (>1 mg/L) in burned transects likely persisted due to slower plant absorption, as PO_4^{3-} is not as biologically mobile as N (Knoepp *et al.* 2009). Accounting for the significant pulse of NH_4^+ makes any P loss or immobilization ecological insignificant in terms of impact on plant growth and regeneration.

2.5 Conclusions

This study offered insight into the immediate responses of sub-surface nutrient pools in a yellow pine forest to low-severity prescribed fire. It is the conclusion of this study the nutrient responses observed are indicative of healthy forest nutrient cycling processes

and that fire-induced increases in nutrients are unlikely to impact forested watershed resources. The prescribed fires had no discernable effect on soil solution NO_3^- , as NO_3^- is highly mobile and requires low volatilization energy. The N behavior observed in this study suggests that fire is beneficial to the yellow pine over story by culling competitive vegetation and reducing nutrient pools. Slight pH buffering in burned transects may have played a role in elevated PO_4^{3-} concentrations, but it is unlikely that the observed PO_4^{3-} response to prescribed fire will impact watershed resources due to functionally inhibited leaching in acidic soils. The generally acidic pH across the site may confer a PO_4^{3-} sink due to the tendency of PO_4^{3-} bind to soil metal cations at low pH. This study suggests that when prescribed fire is applied during the early growing season it causes a benign pulse of nutrients in an otherwise N limited ecosystem. The enhanced productivity is indicative of robust ecosystem response to disturbance and highlights the utility of prescribed fire in maintaining yellow pine forests in the Southern Blue Ridge Mountains.

2.6 Study Limitations and Future Considerations

Due to contaminated pH in lysimeters from residual bleach cleaning solution (Discussed in section 2.2.4) the pH data in this study may not be accurate, but the trends and differences are still representative of how soil solution pH responded to burning. The recalibration method used showed that pH recordings during the first week of sampling may have been off by nearly 4 units. This had implications for nutrient data, as phosphate availability is strongly influenced by pH (Gray 2006, Kutiel & Shaviv 1989). While the

pH trends observed in this study reflect accurate response to burning, parameter values are likely skewed.

This study was further limited by using only one reference control, as the other designated control site was unintentionally burned. A paired study design where every burned transect has a corresponding control transect would make comparison between burned and un-burned transects much more robust. Additionally, this study was conducted in a high order ephemeral watershed and there was limited precipitation following the fire and consequentially no consistent flow in the main drainage. Greater insight into nutrient movement may be gained by collecting and measuring nutrient in sediment or surface runoff after the fire.

CHAPTER THREE: Burn Severity Effects on Sediment and Nutrient Exports from
Southeastern Forests using a Simulated Rainfall Experiment

An Experiment Conducted Summer 2019

Abstract

Burn severity, or the amount of fuel consumed during fire, is an important indicator of post-fire surface runoff and erosion, yet few studies have examined the effects of burn severity in the distinct fire-adapted forests of the Southeastern United States. This study examined the effect of burn severity on erosion and nutrient response in three different fire-adapted forest types of the Southeast. Burn treatment was applied to soil and litter samples to achieve different levels of severity, ranging from very low – only minor charring – to high – characterized by intense heating and total litter consumption. We applied simulated rainfall to experimentally burnt, small litter samples collected from pine, hardwood and mixed hardwood-pine forests in the Clemson Experimental Forest in Clemson, SC. Runoff and leachate samples were collected from the custom-built sample mount and runoff was analyzed for sediment yield (kg/ha), total suspended solids (g/L); both runoff and leachate samples were analyzed for ammonium (NH_4^-), nitrate (NO_3^-) and orthophosphate (PO_4^{3-}). Sediment yield and total suspended solids increased at only the highest burn severity treatment in all three forest types, with pine litter samples yielding significantly greater sediment in surface runoff than both mixed and hardwood samples. Burn treatment did not readily affect soluble nutrient concentrations in either runoff or leachate, but the data suggest that burning increases the availability of PO_4^{3-}

bound to sediment. This study highlights the susceptibility of high-severity burned patches to erosion across a landscape, but highlights the effectiveness of retained litter at small spatial scales at reducing surface runoff.

3.1 Introduction

In undisturbed forests, surface runoff velocity is low, and infiltration is high following precipitation, making forested watersheds valuable sources of clean water. The removal of insulating leaf litter during wildfire or prescribed fire makes underlying forest soils more susceptible to erosion, which is strongly associated with water quality concerns (Certini 2005). Post-fire runoff can compromise water quality from forested watersheds by transporting constituents such as sediment or inorganic nutrients into surface water (Hallema *et al.* 2018, Neary *et al.* 2005). Fine suspended sedimentation is harmful to aquatic organism physiology and siltation can reduce reservoir capacity; increased nutrient concentrations, such as biologically available forms of nitrogen (N) or phosphorous (P), pose eutrophication risks and can be toxic to aquatic organisms at high concentrations (Hallema *et al.* 2018, Warrington *et al.* 2017). The increased risk of post-fire erosion in forests, and subsequent water quality concerns, can be attributed to fire-induced alterations to physical and chemical soil properties and the deposition of an easily erodible ash layer following litter combustion (Cawson *et al.* 2015).

Post-fire erosion increases in forests are strongly associated with burn severity, which is commonly assessed in terms of fuel consumption, as greater fuel consumption exposes underlying soils to more intense heating and the erosive impact of rainfall (Keely 2009, Debano 2000). High severity wildfires can affect the hydrology of entire watersheds but burn severity and subsequent erosion following fire is affected by a variety of environmental factors including fuel moisture, topography, precipitation timing and fuel

composition at various scales (Cawson *et al.* 2013). Burn severity, while largely qualitative, can be manipulated in both wildland, by controlling ignition patterns or seasonality, and experimental conditions, by burning varying degrees of fuel (Keeley 2009). Contemporary knowledge supports the notion that sediment yield increases with burn severity (Johansen *et al.* 2001), and that low burn severities are often achieved during prescribed fire ignition, yet there is limited experimental data on sediment and nutrient response to burn severity in the fire-adapted forest communities of the southeastern United States (Hahn *et al.* 2018; Vose *et al.* 2005).

Forests of the southeastern United States host a diversity of tree species and distinct ecological communities, many of which were either historically fire-dependent or fire-adapted (Nowacki & Abrams 2008). Fire-adapted forest communities in the Southeast can be broadly described as pure stands of hardwoods or yellow pines, and mixed stands of both tree types. Prescribed fire is commonly used in the southeastern United States to prevent the risk of wildfire or maintain fire-adapted vegetation structure in distinct forest types (Elliot *et al.* 2005). While low severity burns rarely cause significant erosion (Anderson *et al.* 2011, Cawson *et al.* 2012), different fuel properties, such as moisture or density, can result in different post-fire constituent response, warranting the comparison of erosion response from different forest types. Additionally, this study aims to highlight the effectiveness of litter retention at lower severity burns at mitigating erosion response; severely burned patches across a landscape can function as sediment and other water quality variable sources during precipitation, while patches of retained litter may be functional sediment sinks (Binkley 1991, Cawson *et al.* 2012).

This study focused on the effect of burn severity on the water quality variables: sediment yield, total suspended solids (TSS) and limiting macronutrients including ammonium (NH_4^+), nitrate (NO_3^-) and phosphate (PO_4^{3-}). We used a custom-built Rainfall Simulator (RFS) to collect sediment and nutrient data from litter samples burnt at increasing degrees of severity to better understand how different forest litter types respond to different burn severities in a controlled environment with few compounding variables. Runoff and leachate were collected from experimentally burnt pine, hardwood and mixed hardwood-pine soil and litter samples. Our goal was to test the following hypotheses:

- (i) Sediment yield in runoff increases with burn severity in all forest types;
- (ii) N concentrations in runoff and leachate will increase with burn severity;
- (iii) P concentrations in runoff and leachate will increase with burn severity.

3.2 Methods

3.2.1 Sample Collection

We used a control-impact experimental approach to determine the effect of burn severity on sediment and nutrient exports in runoff and leachate. Intact samples of litter, duff and the first 5cm of soil were collected from pine (Pine) hardwood (Hardwood) and mixed hardwood-pine (Mixed) forests. Samples were stored in 30x24x10 cm metal trays. P litter samples were collected from pure stands of yellow pine (*Pinus sp.*). Hardwood litter samples were collected from a mixed oak forest with an overstory composed of an assemblage of hardwoods including white oak (*Q. alba*), scarlet oak (*Q. coccinea*), tulip poplar (*L. tulipifera*), beech (*F. grandifolia.*) and hickory (*Carya sp.*). Mixed litter samples were collected from a forest with a canopy composed of both *Pinus sp.* and hardwood assemblages. All samples were collected in the Clemson Experimental Forest (34.6469°, -82.8307°); soil samples from all three forest types were acidic (Table 3.1) Cecil-Hiawasse-Pacolet series formed from the southern piedmont intermediate felsic parent material (USDA 1997).

Table 3.1: Summary of soil and litter pH, total P and Total Kjeldahl nitrogen (TKN) collected from representative forest types in the Clemson Experimental Forest in Clemson, SC. Values are means with standard deviation in parentheses.

Forest Type	Sample Type	pH	Total P (kg/ha)	TKN (ppm)
Pine	Soil	5.0 (0)	7.57 (2.43)	0.6 (0.58)
	Litter	5.4 (0.35)	8.97 (1.59)	0.83 (0.06)
Hardwood	Soil	4.6 (0.15)	5.98 (0.56)	0.42 (0.12)
	Litter	4.4 (0.11)	12.05 (0.49)	1.43 (0.15)
Mixed	Soil	3.9 (0.11)	11.2 (5.26)	0.62 (0.25)
	Litter	4.4 (0.25)	15.13 (4.23)	1.53 (0.2)

3.2.2 Sample Treatment

Samples were burned at four different levels of severity (Table 3.2), ranging from very low (V), low (L), moderate (M), high (H) and an unburned control (C). Severity classes were consistent with descriptions from the Southern Blue Ridge Fire Learning Network (SBRFLN). Samples were burned with an extended propane torch; the torch was held ~15 cm above the samples. Burn severity treatment was applied by increasing flame exposure time. V and L samples were burned on average for <5 second and representative of a low-severity prescribed fire. M samples were burned 5-10 seconds, H samples were burned 10+ seconds or until all organic matter was consumed and were representative of a sever wildfire (Figure 3.1). Each burn severity was replicated 4 times from each litter type, for a total of 60 burned samples. Samples were covered and stored indoors for 48 hours after burn treatment and before rainfall application.

Table 3.2: Description of the four burn severity and control classes used in the RFS experiment.

Burn Severity Class	Description
0: Control	No burn/control
1: Very Low	Litter partially blackened with no structural changes to the leaf matter or duff
2: Low	Litter charred or partially consumed with no changes to duff
3: Moderate	Litter is completely removed with ash deposition and charred duff layer
4: High	Complete consumption of all litter and duff

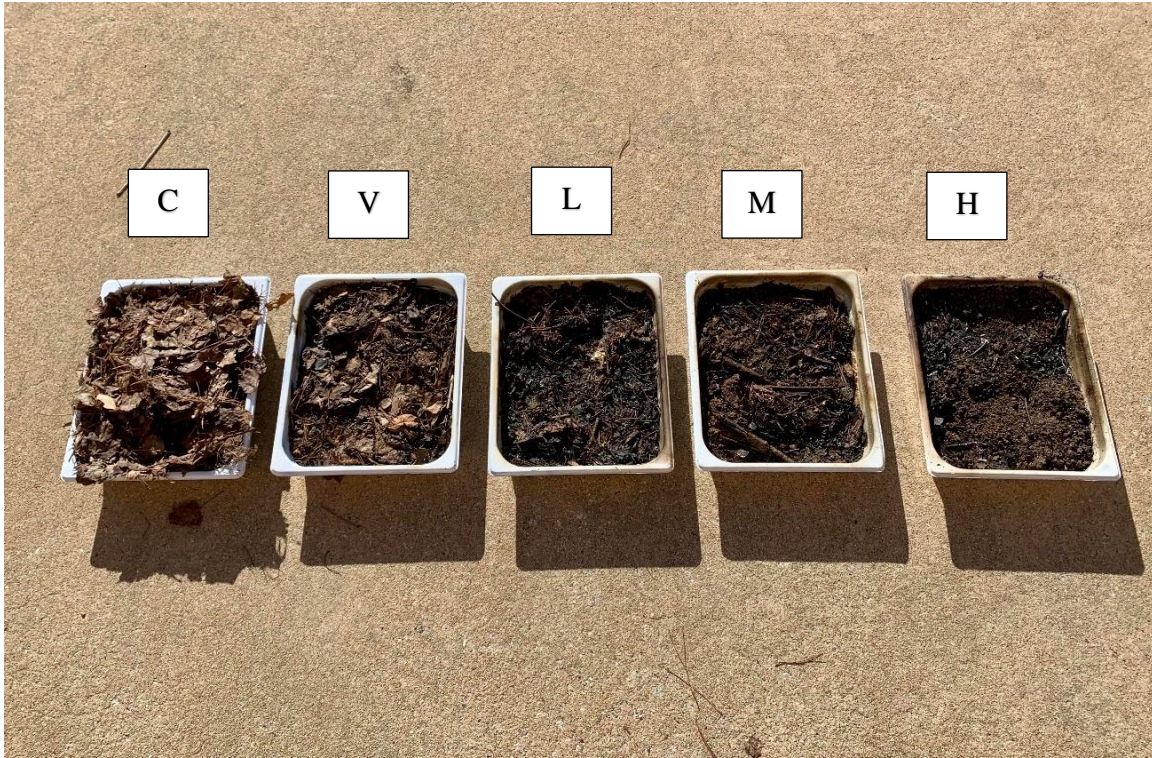


Figure 3.1: Mixed litter samples experimentally burnt to Very Low (V), Low (L), Moderate (M) and High (H) burn severity treatment with unburn Control (C) samples.

3.2.3 Simulated Rainfall

We used a custom-built rainfall simulator and sample mount to collect sediment and nutrient data from experimentally burnt samples (Figure 3.2) We applied simulated rainfall to two sample trays at a time mounted at 100% slope approximately 60 cm beneath the RFS nozzle. (Figure 3.3). Simulated rainfall was applied at rate of 13 mm h^{-1} for one minute delivering approximately 6 liters of water over an area of approximately 1 m^2 . Before application of rainfall, distilled water was buffered to a pH of 6.3, representative of precipitation pH in Pickens County, South Carolina between May-June



Figure 3.2: RFS sample mount with two Low-severity treatment Pine litter samples. Guard rails prevent runoff loss and a cover was placed over collection buckets to prevent sample saturation.

2019. Runoff was collected from a sample area of 735cm² (30.5 x 24.1 cm); leachate samples were collected via a hole drilled into the downslope end of the sample tray. Total runoff and leachate volume were collected and recorded in milliliters. Runoff and leachate samples were swirled to homogenize sediment distribution and two 50 mL subsamples were collected in 55 mL plastic vials to analyze for sediment and nutrient concentrations. Only nutrient concentrations were recorded from leachate samples.

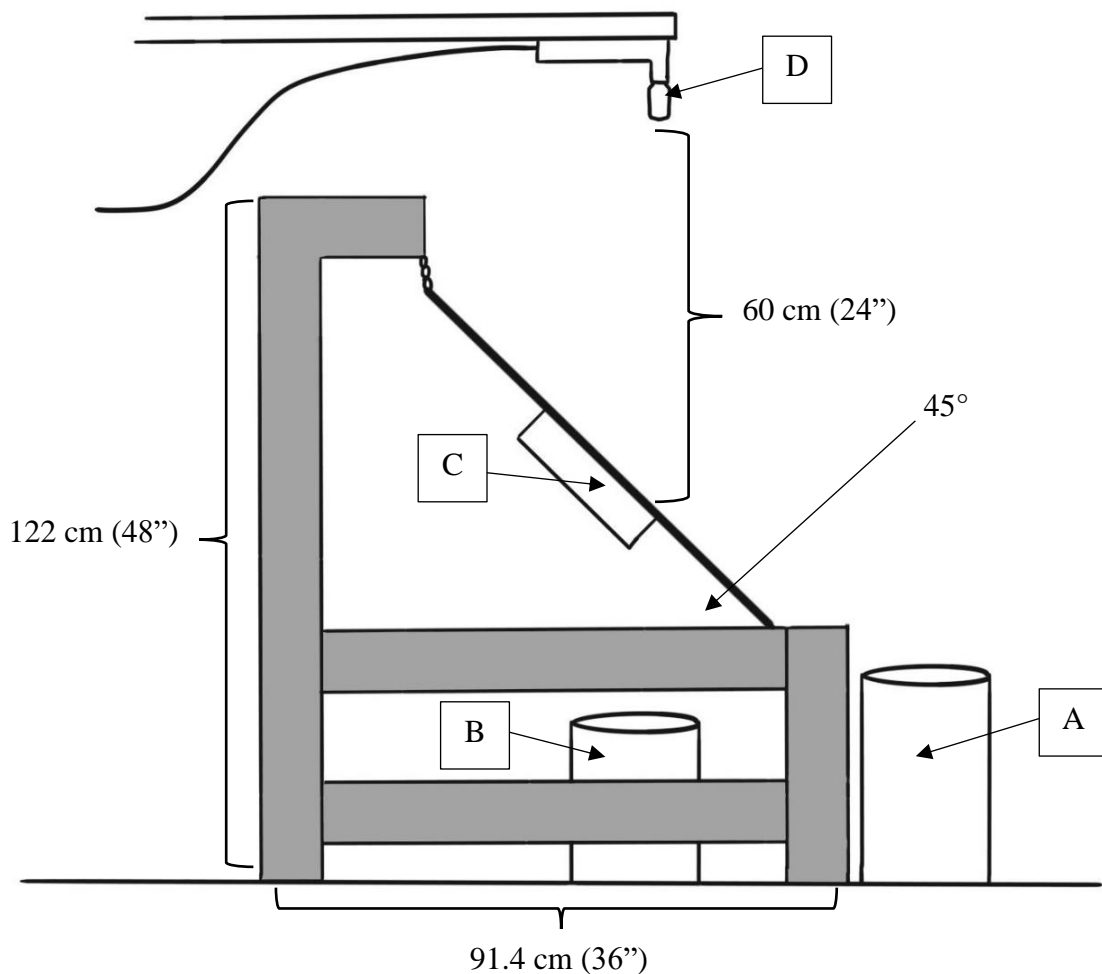


Figure 3.3: RFS profile view diagram and dimensions (inches and centimeters) with runoff collection bucket (A), leachate collection bucket (B), mounted sample (C) and spray nozzle (D). The sample was mounted at an angle of 45°.

3.2.4 Sediment Analysis

Sediment from one runoff sample was filtered and dehydrated at 90 degrees Celsius for 24 hours. Dry sediment load (mg) was measured by subtracting filter paper weight from the final dried sample weight. We calculated TSS (mg/L) by dividing dry sediment (mg) by sample volume (mL) x 1000. We calculated Sediment yield (kg/ha) by dividing total sediment (mg) by the sample area (0.0735 m²).

3.2.5 Sediment Digestion

Sediment from runoff samples were digested to further analyze PO₄³⁻ response to burn treatment. Dry sediment was filtered from C, L and H runoff samples and dried for 24 hours at 75 degrees Celsius. Dried sediment was weighed (mg) and PO₄³⁻ was extracted using EPA 3050B acid digestion method. We used 5 mL of 3 molar nitric acid (HNO₃) to digest dry sediment samples for two hours at 95 degrees Celsius. Digested solution was mixed with 5 mL distilled water and analyzed for PO₄³⁻. Nitrogen forms could not be analyzed in sediment using this method due to the use of HNO₃ to digest sediment.

3.2.6 Nutrient Analysis

We measured NH₄⁺, NO₃⁻ and PO₄³⁻ concentrations (mg/L) in one 50 mL runoff and leachate samples with a FIALab Flow Injection Analyzer-1000 (FIAlyzer) with a detection threshold of 0.005 mg/L. Total nutrient yield (mg) was calculated by dividing concentration (mg/L) by the sample volume (mL). We calculated NH₄⁺ (g/ha) and PO₄³⁻ (g/ha) yield in runoff by dividing total sediment (mg) by the sample area (0.0735 m²). PO₄³⁻ was further analyzed in digested sediment samples. Concentrations were recorded

mg/kg of sediment. PO_4^{3-} concentration in sediment were only calculated at C, L and H burn severity treatments due to sampling limitations. Future considerations include collecting numerous (5-7) 55 mL runoff and leachate samples for any contemporaneous analyses and collecting litter during different burn seasons.

3.2.7 Statistical Analysis

Data was analyzed in the statistic software R (RStudio Team 2018. RStudio: Integrated Development for R. RStudio, Inc., Boston, MA). Analysis of Variance (ANOVA) was used to determine significant differences sediment yield and nutrient between and within forest type and burn severity treatment. We ran a Tukey's Honest Significant Difference (HSD) post-hoc test to determine significant differences between burn severity treatments and among forest types.

3.3 Results

3.3.1 Sediment in Runoff

Table 3.3: Mean Total Suspended Solids (g/L) in runoff samples and sediment yield (kg/ha) from burned litter samples (n = 4). Values within columns separated by different letters are significantly different at the 0.05 level and standard deviations are in parenthesis.

Litter Type	Severity	TSS (g/L)	Sediment Yield (kg/ha)
Pine	Control	0.06 (0.03) ^a	2.91 (1.40) ^a
	Very Low	0.37 (0.02) ^a	15.77 (16.67) ^a
	Low	0.45 (0.02) ^a	20.41 (7.14) ^a
	Moderate	0.65 (0.13) ^b	35.39 (19.63) ^b
	High	1.81 (0.4) ^c	116.3 (25.01) ^c
Hardwood	Control	0.04 (0.35) ^a	1.9 (1.3) ^a
	Very Low	0.15 (0.27) ^a	5.46 (2.39) ^a
	Low	0.11 (0.28) ^a	4.32 (3.96) ^a
	Moderate	0.2 (0.18) ^a	8.31 (3.86) ^a
	High	0.98 (0.18) ^b	47.57 (27.12) ^b
Mixed	Control	0.05 (0.49) ^a	1.93 (1.31) ^a
	Very Low	0.04 (0.5) ^a	1.50 (0.91) ^a
	Low	0.02 (0.49) ^a	1.03 (0.31) ^a
	Moderate	0.09 (0.72) ^a	4.11 (4.79) ^a
	High	0.34 (0.84) ^b	21.74 (20.12) ^b

The data support the hypothesis that sediment yield in runoff increased with burn severity, though only at high burn severity treatment (Table 3.3). Sediment yield was significantly greater from high severity burn samples than C, V, L or M samples from all three forest types ($p < 0.01$). TSS differences were similar to sediment yield in all cases (Table 3.3). Additionally, high severity pine samples had greater sediment yield than both hardwood and mixed samples ($p = 0.002$). There were no differences in sediment yield or TSS at C, V, L and M severity treatments between litter types ($p > 0.1$) suggesting that

only the highest severity burn treatment affected sediment yield or TSS in runoff. High severity pine litter samples generated the greatest sediment yield (116.3 kg/ha), which was significantly greater than both hardwood (47.6 kg/ha) or mixed (21.7 kg/ha) samples (Table 3.3).

3.3.2 Nutrient Concentrations in Runoff

The data do not support the hypothesis P or N concentrations in runoff increased with burn severity treatment. NO_3^- concentrations in runoff and leachate were below the FIAlyzer detection threshold of 0.005 mg/L and were not further analyzed. PO_4^{3-} yield and runoff concentrations were unaffected by burn treatment (Table 3.4). NH_4^+ concentrations in runoff were significantly greater than control concentration from high burn-severity mixed litter samples only ($p < 0.001$). The greatest NH_4^+ concentrations were recorded from hardwood samples at V burn severity treatment (3.57 ± 3.84 mg/L), though this was not different from control due to high deviation (Table 3.4).

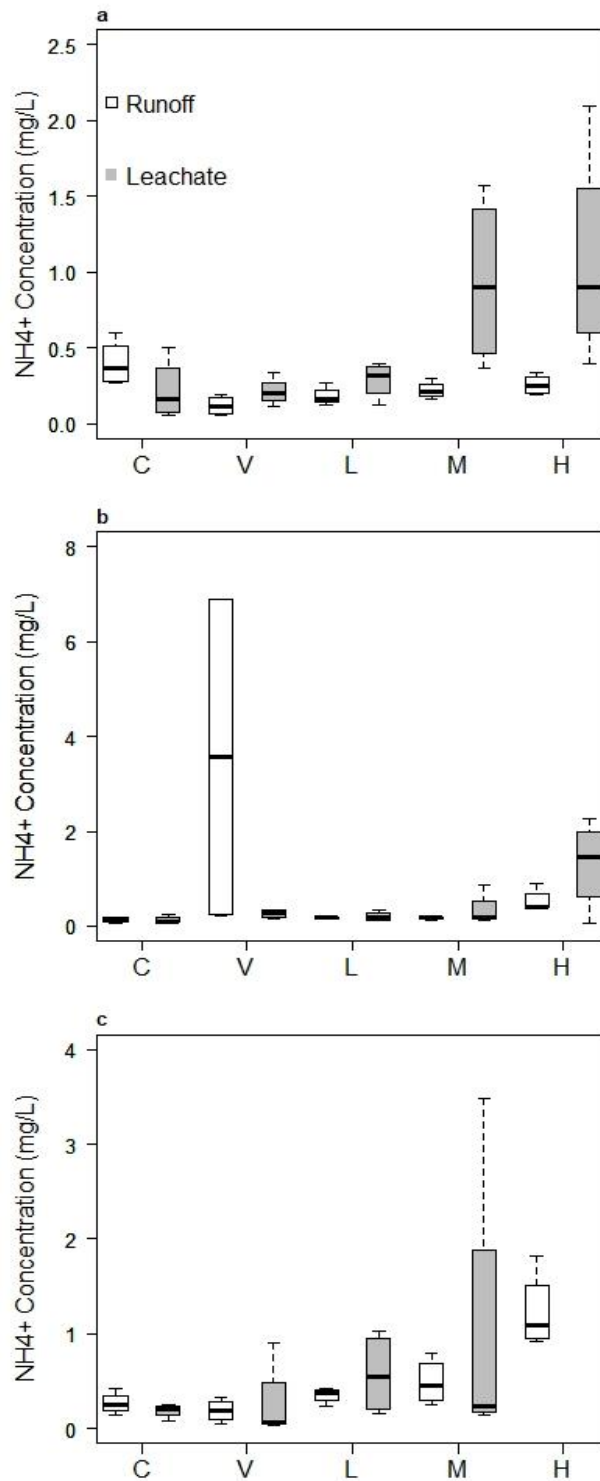


Figure 3.4: Boxplot of NH₄⁺ concentrations (mg/L) in runoff and leachate from pine (a), hardwood (b) and mixed (c) litter samples Control (C), Very Low, (V), Low (L), Moderate (M) and High (H) burn severity treatment.

Table 3.4: Summary of mean NH_4^+ and PO_4^{3-} yield (g/ha) and concentration (mg/L) from runoff samples with standard error in parentheses. Values within columns separated by different letters are significantly different at the 0.05 level.

Litter Type	Severity	NH_4^+	NH_4^+	PO_4^{3-}	PO_4^{3-}
		Yield (g/ha)	Concentration (mg/L)	Yield (g/ha)	Concentration (mg/L)
Pine	Control	22.99 (12.79) ^b	0.4 (0.15) ^b	3.02 (1.8) ^a	0.05 (0.04) ^a
	Very Low	5.35 (3.77) ^a	0.12 (0.07) ^a	14.04 (8.46) ^a	0.33 (0.3) ^a
	Low	8.16 (2.91) ^b	0.18 (0.06) ^a	13.14 (8.9) ^a	0.29 (0.21) ^a
	Moderate	14.14 (7.27) ^b	0.22 (0.06) ^b	3.47 (3.0) ^a	0.05 (0.03) ^a
	High	16.64 (5.71) ^b	0.25 (0.06) ^b	3.73 (1.9) ^a	0.06 (0.03) ^a
Hardwood	Control	6.70 (3.45) ^a	0.14 (0.06) ^a	2.04 (1.8) ^a	0.04 (0.03) ^a
	Very Low	141.41 (153.78) ^a	3.57 (3.84) ^a	10.28 (9.63) ^a	0.27 (0.26) ^a
	Low	7.25 (1.25) ^a	0.18 (0.03) ^a	6.04 (3.55) ^a	0.14 (0.08) ^a
	Moderate	7.16 (1.55) ^a	0.17 (0.03) ^a	2.07 (2.45) ^a	0.06 (0.05) ^a
	High	27.33 (14.17) ^a	0.53 (0.25) ^a	2.53 (1.74) ^a	0.05 (0.03) ^a
Mixed	Control	11.84 (5.25) ^a	0.27 (0.12) ^a	4.12 (7.79) ^a	0.09 (0.03) ^a
	Very Low	8.95 (7.1) ^a	0.19 (0.12) ^a	11.58 (8.32) ^a	0.25 (0.14) ^a
	Low	20.57 (6.27) ^a	0.35 (0.08) ^a	24.59 (10.95) ^a	0.42 (0.2) ^a
	Moderate	24.64 (12.7) ^a	0.49 (0.03) ^a	14.12 (8.6) ^a	0.28 (0.18) ^a
	High	70.12 (37.23) ^b	1.23 (0.41) ^b	17.74 (10.22) ^a	0.33 (0.15) ^a

Table 3.5: Summary of mean NH_4^+ and PO_4^{3-} concentration in leachate samples with standard error in parentheses. Values within columns separated by different levels are significantly different at the 0.05 level.

Litter Type	Severity	NH_4^+ Concentration (mg/L)	PO_4^{3-} Concentration (mg/L)
Pine	Control	0.22 (0.2) ^a	0.04 (0.03) ^a
	Very Low	0.21 (0.09) ^a	0.34 (0.12) ^a
	Low	0.29 (0.12) ^a	0.72 (0.26) ^b
	Moderate	0.94 (0.57) ^a	0.37 (0.25) ^a
	High	1.07 (0.73) ^a	0.17 (0.12) ^a
Hardwood	Control	0.13 (0.07) ^a	0.06 (0.05) ^a
	Very Low	0.25 (0.09) ^a	0.45 (0.73) ^a
	Low	0.2 (0.1) ^a	0.1 (0.06) ^a
	Moderate	0.34 (0.35) ^a	0.45 (0.75) ^a
	High	1.3 (0.93) ^b	0.15 (0.16) ^a
Mixed	Control	0.19 (0.07) ^a	0.23 (0.24) ^a
	Very Low	0.27 (0.42) ^a	0.25 (0.22) ^a
	Low	0.58 (0.44) ^a	0.76 (0.5) ^a
	Moderate	1.03 (1.64) ^a	0.13 (0.14) ^a
	High	-	-

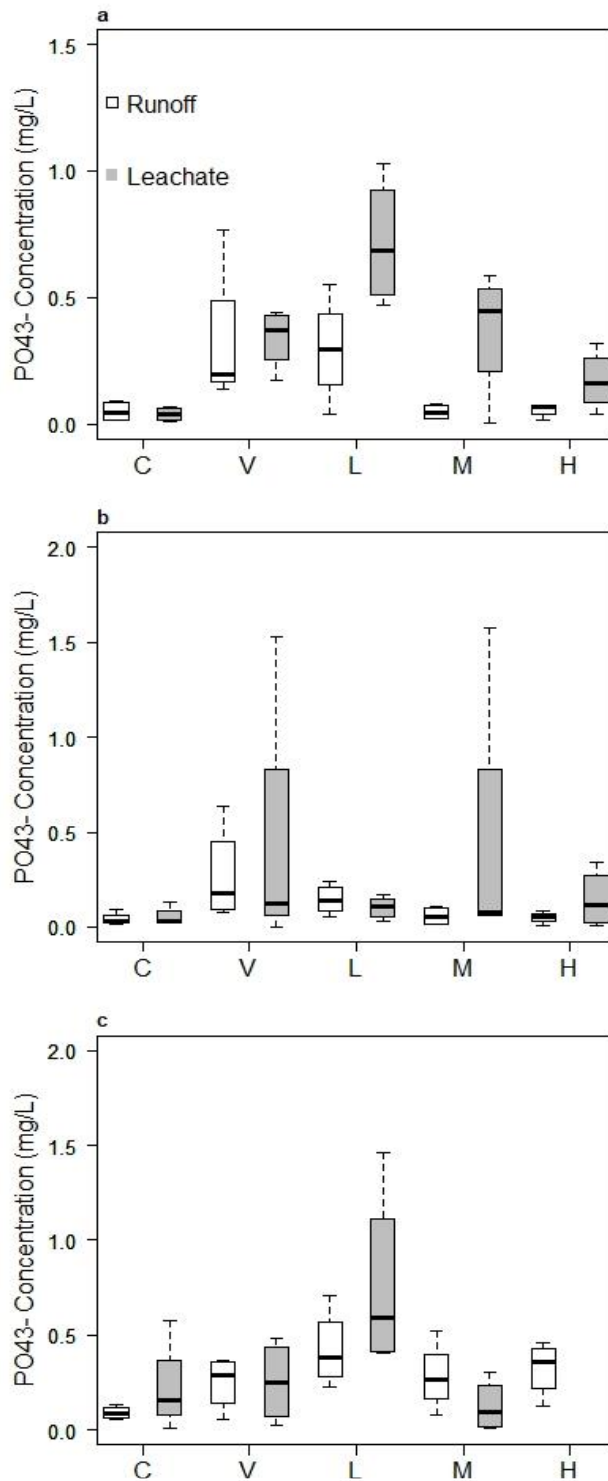


Figure 3.5: Boxplot of PO₄³⁻ concentrations (mg/L) in runoff and leachate from pine (a), hardwood (b) and mixed (c) litter samples at Control (C), Very Low, (V), Low (L), Moderate (M) and High (H) burn severity treatment.

3.3.3 Nutrient Concentrations in Leachate

The data do not support the hypothesis N or P concentrations in leachate increased with burn severity treatment. PO_4^{3-} concentrations in leachate (Figure 3.5) were significantly greater than control concentrations from low-severity pine litter samples only ($P < 0.001$). NH_4^+ concentrations in leachate were greater than control concentrations from high-severity hardwood litter samples only ($p = 0.025$) reaching a maximum concentration of 0.71. PO_4^{3-} and NH_4^+ yield in leachate was unaffected by burn treatment. There was no leachate collected from high-severity mixed litter samples likely due to high water repellency and low initial infiltration (Table 3.5).

3.3.4 PO_4^{3-} concentrations in Sediment

Table 3.6: Summary of mean PO_4^{3-} concentration in sediment (mg/kg) from C, L and H burn severity treatment litter samples with standard error in parentheses. Values within columns denoted by an asterisk (*) are significantly different than the control at the 0.05 level.

Litter Type	Severity	PO_4^{3-} Concentration (mg/kg)
Pine	Control	0.8 (0.3)
	Low	3.49 (2.0)
	High	4.47 (1.5)
Hardwood	Control	2.48 (2.1)
	Low	3.6 (2.6)
	High	9.5 (3.4)*
Mixed	Control	1.05 (0.3)
	Low	5.4 (4.7)
	High	7.8 (4.9)

The data do not suggest that PO_4^{3-} complexation to sediment was readily enhanced by burn severity treatment. Mean PO_4^{3-} concentration in sediment was only greater than control (2.48 ± 2.1 mg/kg) concentrations from high severity Hardwood (9.5 ± 3.4 mg/kg) litter samples ($p = 0.046$). There were no significant differences between litter types at L and H burn severity treatment (Table 3.6). Additionally, PO_4^{3-} yield (kg/ha) in sediment was unaffected by burn treatment (Figure 3.6). While there is limited statistical evidence to support the hypothesis that burn treatment increases the availability of PO_4^{3-} in sediment, general trends indicate that PO_4^{3-} concentrations in sediment increased at more intense or severe burn treatments. However, in this study we found no difference between L and H burn severity treatment on PO_4^{3-} concentrations in sediment.

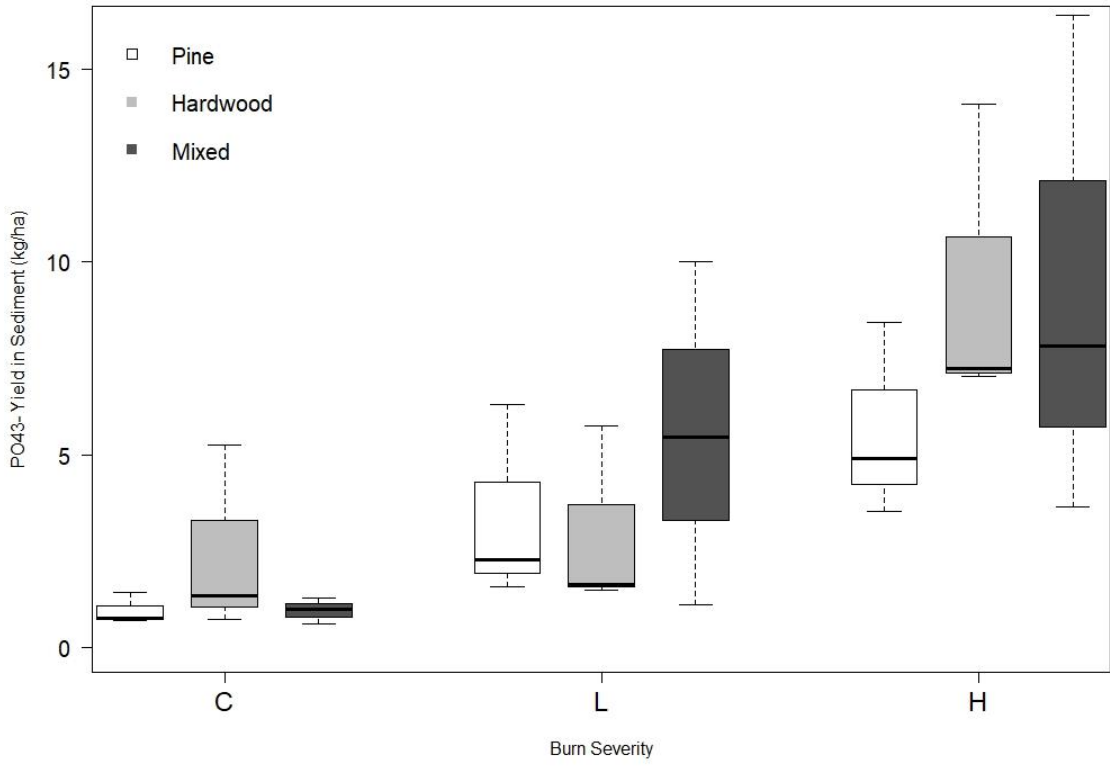


Figure 3.6: Boxplot of PO₄³⁻ yield (kg/ha) from acid digested sediment samples from Pine, Hardwood and Mixed litter samples at Control (C), Low (L) and High (H) burn severity treatment.

3.4 Discussion

3.4.1 Sediment Yield

This study provides sediment yield, TSS and nutrient data in runoff from litter samples from three different forest types burnt to varying degrees of severity. The effect of V, L and M burn severity treatment on sediment yield and TSS was negligible. The results suggest that TSS and sediment yield increase at only high severity burn treatment. While few studies compare sediment yield between forest types, the significant sediment yield increase at only high severity burn treatment is well documented in other forest types (Robichaud & Waldrop 1991, Cawson *et al.* 2012).

The lack of difference between C, V, L and M burn treatment from pine, hardwood and mixed samples suggests that litter retention is an effective mechanism for reducing runoff and subsequent soil movement. In the case of all high severity burn treatments, significant soil heating likely occurred which may have caused the development of hydrophobic, water repellent soil properties (Debano 2000). However, the increased sediment yield and TSS from high severity burned samples in this experiment is likely due to homogenous fuel consumption, as surface cover is an important predictor of erosion response in other forest types (Elliot & Vose 2006, Larsen *et al.* 2009).

The retention of litter at C, V, L and M severity burn treatments effectively slowed runoff velocity in all three litter types, allowing the downward movement of precipitation through the soil. The high-severity burned samples in this experiment are more representative of a severe wildfire, suggesting that low-severity burns cause minimal

sediment loss in surface runoff, irrespective of forest type or litter composition. This study additionally highlights the risk of increased erosion in pine, hardwood and mixed hardwood-pine forests when high severity fuel consumption is coupled with intense precipitation as post-fire erosion is strongly correlated with precipitation intensity and timing post-fire. While Pine litter samples yielded the greatest sediment load, perineal canopy cover in yellow pine forests slows precipitation throughfall – an environmental factor that may naturally limit erosion response in wildland settings. The similar sediment response between forest types at high burn severity further suggests that the removal of insulating litter and organic matter is responsible for increased sediment yield and TSS, as has been documented in other forest types (Cawson *et al.* 2012, Larsen *et al.* 2009). While this study does not account for natural features of the forest floor that may inhibit surface runoff during precipitation events, such as root mats, it suggests that heterogenous fuel consumption effectively reduces sediment mobility after fire in different forest types.

The data indicate that soil loss increases with burn severity, yet the small sample area must be considered when assessing possible causes of increased erosion, as Larsen *et al.* (2009) postures that post-fire soil water repellency manifests at smaller spatial scales. Fire-induced soil hydrophobicity is often neutralized after initial exposure to precipitation and precipitation on severely burnt patches causes erosion due to the lack of insulating litter rather than permanent soil water repellency (Larsen *et al.* 2009). This study suggests that high severity burn patches may act as significant sediment sources during precipitation due to the removal of protective litter cover. However, sediment yield at a

landscape scale is likely lower than in this study as retained litter, which is common in moist riparian zones, reduces surface runoff velocity and prevents major sediment movement (Blake *et al.* 2009, Cawson *et al.* 2012). An important insight is that although sediment yield increased at High burn severity treatment, there was relatively little soil loss.

3.4.2 Nitrogen

Nutrient concentrations in runoff and leachate only increased compared to control concentrations in a few situations, with no clear patterns. Combustion was likely responsible for the total loss of NO_3^- from samples, as NO_3^- is volatilized at temperatures as low as 200 degrees Celsius (Vose *et al.* 2005). However, leaching OH^- ions from the ash layer enabled the transformation of remaining organic N during the 48-hour incubation period, explaining the significant NH_4^+ increases in leachate at high burn severity from pine litter samples. The observed NH_4^+ concentrations in runoff from all forest types were generally greater than the average stream water concentration in undisturbed southeastern streams of approximately 0.07 mg/L (Binkley *et al.* 2004), suggesting some amount of fire-induced mobilization. Elevated NH_4^+ concentrations in runoff or leachate may indicate N loss from the ecosystem, particularly after high severity fire in the absence of plant water uptake (Binkley *et al.* 2004). N saturation in a forest is associated with its own set of risks including soil acidification and eutrophication (Fenn *et al.* 2014); intermittent burning may temporarily reduce organic N pools in forest ecosystems that may have become N saturated due to an extended period without fire. NH_4^+ in soils adheres readily onto negatively charged clay particles, making it less

mobile than NO_3^- and less likely to be transported in surface runoff or leachate (Binkley *et al.* 2004).

The NH_4^+ concentrations and yield from experimentally burned samples in this study suggest that post-fire runoff is not an effective transport mechanism for NH_4^+ contained in organic matter or ash. It also cannot be inferred that burn patches of any severity throughout a landscape function as NH_4^+ sources during precipitation as NH_4^+ movement in all three forest types is minimal due to its tendency to bind to soil anions. In wildland settings, the timing between burning and precipitation is a key variable contributing to both sediment and nutrient transport – the 48-hour incubation period prior to rainfall application likely was not long enough for enough NH_4^+ to accumulate. NH_4^+ response to prescribed fire in wildland settings is likely minor in absence of any intense precipitation directly after fire, and any biologically available NH_4^+ is readily absorbed by regenerating vegetation, as demonstrated in Chapter 2. This study suggests that burn severity treatment has a negligible impact on NH_4^+ in both runoff and leachate.

3.4.3 Phosphorous

PO_4^{3-} concentrations in runoff and leachate from burned samples were generally greater than control concentrations, though only significantly greater in low severity leachate samples. The lack of any notable impact of burning on PO_4^{3-} in surface runoff may be due to its adhesion to soil minerals and oxides and complexation to sediment or ash. Indeed, analyzing digested sediment samples from all three forest types revealed significantly greater PO_4^{3-} in sediment from H severity burn treatment Hardwood samples. General

trends indicate greater PO_4^{3-} yield (g/ha) at L and H severity treatment than control, though there no statistical evidence to support this (Figure 3.6). Another observation is that there was greater PO_4^{3-} yield (g/ha) in surface runoff than there was in sediment, however PO_4^{3-} concentration in sediment (mg/kg) was much greater than surface runoff concentrations (mg/L). This indicates that, while organic P may be readily abundant in un-burned forest litter, burn treatment can increase the amount of available PO_4^{3-} bound to sediment, especially in acidic terrestrial environments, such as the forest types investigated in this study (Table 3.1). This has implications for downstream water quality, as PO_4^{3-} becomes increasingly mobile pH approaches neutrality, meaning that PO_4^{3-} bound to sediment during burning will rapidly solubilize in neutral surface waters (Weil & Brady 2017).

The effect of burn severity treatment on PO_4^{3-} yield and concentrations in runoff and leachate likely does not confer any significant ecological impact as the concentrations recorded during this study were representative of the average stream water concentration in the southeast of approximately 0.02 mg/L (Binkley *et al.* 2004). Additionally, the average PO_4^{3-} concentrations in runoff were well below the Environmental Protection Agency's (EPA) maximum stream water total phosphorous criterion of 0.13 mg P/L (NCASI 2001). A review of available P in stream water by Binkley *et al.* (2004) suggested that PO_4^{3-} exports differ by forest type within geographic regions, however this study found little difference in PO_4^{3-} yield or concentrations in surface runoff within or between forest types. Few studies have examined the impact of burning on soil P, those that have posit that moderate-to-high severity fire causes P loss from a forest system by

means of volatilization or off-site transport, which can impact surface water (Santin *et al.* 2018, Son *et al.* 2015, Stephens *et al.* 2004). This study suggests that post-fire P loss from a forest is not caused by direct volatilization or immediate off-site transportation, but rather by the complexation of mobilized inorganic orthophosphate to soil metal cations in acidic soils ($\text{pH} < 6$).

Greater PO_4^{3-} adhesion to sediment at H burn severity treatment in Hardwood forests does provide evidence of possible P loss and transport into surface water. These findings warrant concern in these forests, as the combination of severe litter consumption, P mobilization and any intense precipitation event could make surface runoff an effective transport mechanism for sediment containing biologically available PO_4^{3-} into surface waters. While increased suspended sediment and soluble PO_4^{3-} in surface waters can impair aquatic ecosystem productivity, yield and concentrations at a watershed scale are likely much lower than in this study due to environmental factors such as stream flow or shade (Warrington *et al.* 2017). This study suggests that low-to-moderate severity burning at in Southeastern forests has minimal impact on inorganic P, yet incorporation of inorganic P into sediment or ash represents a possible P source after high severity burning.

3.5 Conclusions

Specific conclusions that can be drawn from this study include that (i) sediment yield and TSS in surface runoff is greater than unburned forests only at only high burn severity due to the effectiveness of retained litter at reducing surface runoff and (ii) burning had very

little effect on NH_4^+ and PO_4^{3-} concentrations or yield in sediment, leachate or runoff. There was no difference in nutrient yield or concentrations in both runoff and leachate between forest types indicating that nutrient response to burning is similar among distinct forest types in the southeast. However, pine samples burned at high severity yielded more sediment than both hardwood and mixed samples at the same burn treatment. Increased sediment yield and TSS in runoff at only high severity burn treatment demonstrated the effectiveness of retained litter at limiting soil loss following fire in forests. Moreover, the data suggest that erosion and nutrient responses are similar among the distinct fire-adapted forested environments of the southeastern United States. The lack of fire effects on NO_3^- , NH_4^+ and PO_4^{3-} concentrations in surface runoff, and sediment contained in surface runoff, indicates that burn severity treatment did not readily alter or mobilize terrestrial nutrients and that any sustained nutrient increases in surface water are highly unlikely. However, the possibility of PO_4^{3-} complexation onto sediment and subsequent release in surface waters at neutral pH should not be ruled out as a possible source of elevated post-fire PO_4^{3-} in streams or lakes. Fire managers should maintain intact litter patches downslope of high-severity burned patches to reduce surface runoff velocity and sediment transport, though this is often achieved naturally due to mesic litter in riparian areas. Hillslope and watershed scale studies are needed to determine the homogeneity of erosion and nutrient response at greater spatial scales in southeastern forests.

3.6 Study Limitations

NO_3^- and NH_4^+ concentrations in sediment along with sediment pH were not measured because of the nitric acid (HNO_3) digestion method used to extract PO_4^{3-} . The acid digestion would have skewed any N readings and the digested solution pH was contaminated. NO_3^- is likely not adsorbed onto sediment as it is more mobile than both PO_4^{3-} and NH_4^+ . However, future studies should consider analyzing NH_4^+ in sediment, as it can bind to clay particles or oxides in a similar manner to PO_4^{3-} . Examining NH_4^+ adhesion to sediment in runoff could identify a potential NH_4^+ source after prescribed fire.

Rainfall simulation experiments are by nature controlled and adaptable. The methods used in this experiment can be applied to measure sediment and nutrient exports from all variety of experimentally manipulated small litter samples. Future considerations for this study include collecting more runoff samples to measure phosphorous in sediment. General further applications of the RFS study design include assessing how soil water repellency or hydrophobicity at the soil-pore scale may affect erosion in Southeastern forests.

CHAPTER FOUR: Conclusions

4.1 General Conclusions

This thesis examined the effects of prescribed fire and burn severity on erosion and macronutrient availability in the forests of upstate South Carolina. Review of contemporary literature concerning prescribed fire and water quality (Chapter 1) confirmed that low-to-moderate severity prescribed fire causes significant soil movement in many forest types and identified that burn severity and precipitation timing/intensity were the primary indicators of post-fire erosion magnitude. The literature does not suggest that eutrophication or macronutrient movement are significant water quality concerns after prescribed fire, as elevated concentrations were regarded in many circumstances as an Assart effect, or a pulse of nutrients after disturbance which confers little ecological impact. The literature review additionally highlighted that sources and causal agents of post-fire erosion manifest at different spatial scales, and the conceptual model (Figure 1.1) suggests that the magnitude of prescribed fire effects on constituent export in forested watersheds is dependent on (i) burn severity, (ii) precipitation timing and intensity, and (iii) the scale at which constituents are measured. Hypotheses were derived from the conceptual model and tested at different spatial scales including watershed-scale study examining sub-surface nutrient pool response to burning (Chapter 2) and a rainfall simulation experiment (Chapter 3). Overall, results from the field and experimental studies in this thesis showed that:

- (i) Low-severity prescribed fire can temporarily increase sub-surface NH_4^+ and PO_4^{3-} concentrations in upland yellow-pine forests in the Southern Blue Ridge Mountains;
- (ii) Low-severity prescribed fire can temporarily buffer soil pH towards neutrality;
- (iii) Low-to-moderate burn severity had relatively little effect on post-fire sediment yield – sediment yield increased at only the highest burn severity treatment;
- (iv) Retained litter at low-to-moderate burn severity were effective at reducing sediment yield in surface runoff;
- (v) Prescribed fire has little-to-no effect on NO_3^- due to the low temperature at which it is volatilized to the atmosphere;
- (vi) Fire can increase the biological availability of NH_4^+ and PO_4^{3-} at both the landscape and small-plot scale, though these increases are minor and ephemeral.

4.2 Effects of Prescribed Fire on Sub-Surface Nutrient Pools

The results from the field study (Chapter 2) highlight the heterogeneity of nutrient pool and soil chemistry response to prescribed fire across a landscape. Despite dangerously high predicted peak concentrations of NH_4^+ and an extended period of elevated PO_4^{3-} , high variability across the burned landscape resulted in only temporary increases relative to control sites. The significant pulse of NH_4^+ and PO_4^{3-} , along with the slight pH

buffering observed in burned transects suggests that prescribed fire *does*, at least temporarily, alter sub-surface nutrient pools though the downward movement of volatilized organic matter and the release of oxides. While this may warrant concern for downstream watershed resources, it is the conclusion of this thesis that the increases observed in this study did not confer any ecological degradation and were likely beneficial to the forest at the onset of the growing season.

While a significant pulse of NH_4^+ and PO_4^{3-} was detected approximately a week post-fire (Chapter 2), nutrient concentrations in leachate were unaffected by burn severity treatment in the simulated rainfall study (Chapter 3). A likely explanation for this is that the 48-hour period between burn treatment and rainfall application was not long enough for NH_4^+ to pool. Additionally, the lysimeters collected soil solution (Chapter 2) from 30 cm depth, while the small plot samples only contained the first 5 cm of mineral soil. Chapter 2 of this thesis highlights the temporal disparity between fire occurrence and nutrient response. While this thesis suggests that low-severity prescribed fire can increase sub-surface nutrient pool concentrations, it is important to recognize the high variability in the distribution of enhanced nutrient pools across the burnt landscape and that sub-surface macronutrient movement is functionally inhibited in the forest types examined in this study. Any alteration to sub-surface nutrient pools after prescribed fire are likely minimal, heterogeneously dispersed and likely beneficial to regenerating vegetation at the start of the growing season.

4.3 Effects of Burn Severity on Small Litter Samples Sediment Yield

The literature review and conceptually diagram suggest that burn severity is the primary indicator of post-fire erosion response. However, the small plot rainfall simulation study (Chapter 3) found that sediment yield and TSS increased at only the highest severity, suggesting that post-fire erosion is less dependent on burn severity at low-to-moderate severity. It can be inferred that high severity burn patches function as sediment sources across a burnt landscape, though environmental variables, such as retained canopy cover that reduced precipitation throughfall velocity in pine forests, can affect the magnitude of erosion response. This study was unable to determine the erosion potential of low-to-moderate severity burn patches across a burnt landscape, as there was no difference from the control. Similar studies have shown that mesic riparian corridors inherently exclude low-intensity fire and retained, unburned litter significantly reduces runoff downslope from prescribed fire. This thesis suggests a similar response pattern in Southeastern forests, and management considerations include targeting heterogeneous low-to-moderate severity burns, as litter retention at lower burn severities effectively reduced sediment yield in surface runoff in this thesis. Future avenues of research to identify specific post-fire sources of erosion in Southeastern forest types includes hillslope-scale measurements of erosion and sediment yield, in-stream sediment sampling, examination of hydrologic connectivity across a heterogeneously burned landscape and the viability of less severely burned patches at reducing surface runoff.

4.4 Fire effects on Macronutrients in Runoff

Burn severity treatment had very little effect on NH_4^+ , NO_3^- and PO_4^{3-} concentrations in runoff collected during the rainfall simulation experiment (Chapter 3). The lack of any appreciable increase is because any available NH_4^+ and PO_4^{3-} in the burned litter samples was likely became bound to sediment oxides or minerals during burning. Acid digestion revealed significantly greater PO_4^{3-} in high severity burn treatment sediment from Hardwood litter samples which suggests burning can cause the direct adhesion of inorganic P to soil particles. The implication for water quality is that biologically PO_4^{3-} bound to sediment easily disassociates from sediment at neutral pH, making sediment from high-severity burned patches a possible PO_4^{3-} source if it is transported into perineal surface waters. PO_4^{3-} complexion onto sediment and significantly greater sediment yield at high burn severities suggests that surface runoff containing this sediment may be an effect PO_4^{3-} transport mechanism into surface water, which poses direct eutrophication risks as soluble PO_4^{3-} is the primary nutrient limiting aquatic ecosystems. However, once again it is important to recognize environmental factors that may mitigate any P inputs into surface waters, such as shaded streams, where algal growth is limited by access to sunlight, or dilution in fast-flowing water. Future considerations include further analysis of PO_4^{3-} in digested sediment from runoff, as nutrient complexion to soil particles is the most likely mechanism by which excess post-fire nutrients are transported rather than direct incorporation into surface runoff.

4.5 Overall Conclusions

The overall objective of this thesis was to determine if prescribed fire negatively effects water quality in the forests of the Southern Appalachians. This was accomplished by examining sediment nutrient exports – important water quality variables – at various spatial scales. Overall, sediment and nutrient response to prescribed fire was low, suggesting that low-to-moderate severity prescribed fire has little effect on water quality in general. Specific conclusions that can be drawn from this thesis include:

- (i) Prescribed fire does cause significant nutrient loss from a forest ecosystem and temporarily elevated sub-surface nutrient pools are beneficial to forest health as nutrient leaching is limited in the acidic soils of the Southeast;
- (ii) Runoff and sediment yield may increase from burnt patches relative to unburnt patches, but only at high burn severity treatment where the effects of water repellency may be more pronounced;
- (iii) Retained litter at low-to-moderate burn severity prevents significant erosion in the Pine, Hardwood and Mixed hardwood-pine forests of the Southeast;
- (iv) Sedimentation or eutrophication risks exist only when high-severity burning is coupled with intense precipitation: in the absence of precipitation sediment and macronutrient movement is greatly limited.

CODA

This thesis examined the effect of prescribed fire and burn severity on water quality variables (i) sediment yield and (ii) macronutrient concentrations at varying spatial scales. It was the goal of this thesis was to fill a contemporary knowledge gap in how forests of the Southern Appalachians respond to prescribed fire. Empirical data showed that prescribed burning temporarily increased sub-surface N and P pools; that burn severity only confers increased erosion at the highest burn severity treatment; that litter retention is effective at reducing surface runoff and that macronutrient availability is limited by prescribed fire. In a word: Fire, good.

I have always respected fire and this thesis has allowed me an opportunity to intimately examine this powerful force of the natural world. Prescribed fire in the Southeast is applied to benefit forest health and maintain their valuable services, and I believe this thesis has effectively illustrated the *lack* of negative effects prescribed fire has on water quality. It is my fervent hope that this thesis opens future avenues of research monitoring how prescribed fire *benefits* the forests of the Southeast. All too often, I believe, research questions are antagonistic – we develop hypotheses to show that a practice is causing ecological detriment or to highlight potential sources of pollution. I hope this thesis highlights the utility of prescribed fire and enables the development of research questions to quantify how prescribed fire *improves* Southeastern forest health.

APPENDIX

Appendix A:

Summary table from chapter 2 of basal area (BA), trees pre acre (TPA), quadratic mean diameter (QMD), tree diameter and height by stand, transect and condition in Jocassee Gorges Management Area. Data were collected on February 20th, 2019. Tree species was loblolly pine (*P. taeda*).

Stand	Transect	Condition	BA (sq. ft)	Stand Density (TPA)	QMD (in)	Min Diameter (in)	Max Diameter (in)	Mean Height (ft)	Min Height (ft)	Max Height (ft)
1	1	Burn	85	101	12.4	8.9	16.8	60.9	54	69
1	2	Burn	80	92	12.6	9.7	17.3	62.2	55	71
1	3	Burn	70	90	12.0	8.6	17.1	60.1	53	71
1	4	Burn	65	93	11.3	7.4	15.0	58.2	50	63
1	5	Burn	75	113	11.0	7.4	16.3	56.0	48	65
2	6	Control	70	77	12.9	10.8	15.2	60.2	52	67
2	7	Control	70	85	12.3	7.9	16.4	57.9	48	66
2	8	Burn	75	92	12.2	9.2	15.2	58.7	52	68
2	9	Burn	80	104	11.9	7.8	16.4	61.3	55	70

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