Pre- and Post-Fire Soil Comparisons

ROGERS RESEARCH SITE, NORTH LARAMIE MOUNTAINS, WYOMING

By Stephen E. Williams, Claire D. Wilkin, Linda T.A. van Diepen,
Larry C. Munn, Michael A. Urynowicz, and Robert W. Waggener

University of Wyoming
Agricultural Experiment Station

Rogers Research Site Bulletin 7
December 2018

ROGERS RESEARCH SITE BULLETIN 7: Pre- and Post-Fire Soil Comparisons, Rogers Research Site, north Laramie Mountains, Wyoming

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Layout and design by Tanya Engel

University of Wyoming College of Agriculture and Natural Resources

Wyoming Agricultural Experiment Station

This is Bulletin 7 in an ongoing series focusing on research, teaching, extension, and other activities at the University of Wyoming's Rogers Research Site (RRS) in the Laramie Mountains, north Albany County, Wyoming. The approximate 320-acre site was bequeathed to UW in 2002 by Colonel William Catesby Rogers.

Colonel Rogers spent much of his retirement time at the mountainous, remote property, which he called the Triple R Ranch. UW renamed the property "Rogers Research Site" in memory of Colonel Rogers, who passed away in 2003 at age 96.

The February 16, 2002, amended living trust of Colonel Rogers states that:

> said ranch be used for the public benefit as a center for studies, a retreat for conducting meetings, conducting conferences, or conducting research in connection with the improvement of wildlife and forestry, or to hold as a natural wooded area in its original state with specific instructions that no part of it be subdivided or sold for residential or private business purposes but held as an entire tract. Said restriction is to continue in perpetuity. If violated, said property shall revert to the ownership of the U.S. Forest Service.

Overseeing management of RRS is the Wyoming Agricultural Experiment Station (WAES), UW College of Agriculture and Natural Resources. RRS is placed administratively under one of the WAES research and extension centers, the James C. Hageman Sustainable Agriculture Research and Extension Center (SAREC) near Lingle, Wyoming.

SUGGESTED REFERENCE

Williams, S. E., Wilkin, C. D., van Diepen, L. T.A., Munn, L. C., Urynowicz, M. A., and Waggener, R. W., 2018, Pre- and post-fire soil comparisons, Rogers Research Site, north Laramie Mountains, Wyoming: University of Wyoming, Wyoming Agricultural Experiment Station, Rogers Research Site Bulletin 7, *iv* + 34 p.

ON THE COVER

University of Wyoming students taking a 2012 forest and range soils course taught by lead author Stephen E. Williams examine soil properties at the Rogers Research Site approximately three months after the Arapaho Fire burned across the site. Their examination included soil texture (determined by hand), pH, electrical conductivity, and depth of soil horizons. (Photo by S. Williams)

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Issued in furtherance of State Agricultural Experiment Station work of the 1887 Hatch Act, as amended through public law 107–293, November 13, 2002, in cooperation with the U.S. Department of Agriculture. Bret Hess, director, Wyoming Agricultural Experiment Station, University of Wyoming, Laramie, Wyoming 82071.

CONTENTS

ABOUT THE AUTHORS

STEPHEN E. WILLIAMS

Professor Emeritus Steve Williams came to the University of Wyoming in 1976 as a newly minted Ph.D. and an assistant professor of soil science. During one of his countless outings in Wyoming's big outdoors—this time an early spring 2017 adventure to Difficulty Canyon near the Freezeout Mountains—Williams reflected on his nearly four-decade career at UW.

"At UW I was able to renew long-standing interests in forest, range, and wildland soils. Now, looking back, I realize how much I learned from other faculty, and also from my students, including those I worked with at the Rogers Research Site (RRS).

"My professional life, made possible at UW, included projects in the high-elevation sagebrush steppes and the crags of the Wind River Range; among the cultural horizons in soil pits at Hell Gap; and in the forests of the Black Hills, coal mines at the Jim Bridger Plant, and acid basins of Yellowstone National Park, to name a few. My career at UW has been nothing short of fantastic, and I have the people and institutions of the state to thank for that.

"Late in my career at UW, I started work at the RRS, a new site slated for forestry- and wildlife-related research in the Laramie Peak area of southeast Wyoming. The ecosystems at RRS have taught me much, but I am cowed in the face of what we do not know.

"More recently I got to know of the man, Colonel William C. Rogers, who bequeathed this land to UW. Further, I am awed by the man who gifted this to UW, to the people of Wyoming—and to me."

Williams, who earned a Ph.D. in soil science from North Carolina State University in 1977, was on more than 140 graduate committees during his tenure at UW, and he authored or co-authored approximately 50 peer-reviewed publications.

He has been at the center of much of the early work associated with RRS, including planning and research. This publication marks his fifth co-authorship in the peer-reviewed RRS bulletin series, and an upcoming bulletin expanding on the post-fire soils research at RRS will mark his sixth.

Since retiring in 2013, Professor Emeritus Williams and his wife, UW Professor Emeritus Karen Cachevki Williams, have operated an environmental and educational consulting business based in Laramie, Wyoming.

Professor Emeritus Steve Williams spent countless hours lecturing in the classroom and conducting studies in the laboratory, but he found time every field season to blend his passion studying soils, collaborating with scientists, and mentoring students with hikes across rangelands, forests, and high-mountain wilderness. Those treks took him throughout Wyoming and to the forests and rangelands of California, Mongolia, New Zealand, and beyond, where he was involved in everything from mine land reclamation to improving the health of kauri forests

Claire Wilkin began a soils research project at the Rogers Research Site (RRS) in 2011 while working on her M.S. degree at the University of Wyoming. In summer 2012, her project took a major turn when the Arapaho Fire burned approximately 98,000 acres (~39,700 hectares) in the north Laramie Mountains of southeast Wyoming, including the 320-ac (~130-ha) RRS. The lightning-caused Arapaho Fire, which occurred during a severe drought, would give Wilkin and team members a chance to study a post-fire ecosystem. Touring RRS before the fire, Wilkin is pictured here with Jim Freeburn, former director of the James C. Hageman Sustainable Agriculture Research and Extension Center, which oversees management of the site under the Wyoming Agricultural Experiment Station.

CLAIRE D. WILKIN

Claire Wilkin is among the University of Wyoming graduate and undergraduate students who have conducted research at or relating to the Rogers Research Site (RRS). While earning her master's degree at UW, Wilkin focused her studies at RRS on pre- and post-fire soil comparisons, work that is detailed in this bulletin; and nutrient additions and soil microbial community recovery following the 2012 Arapaho Fire, work that will be detailed in RRS Bulletin 8. Her faculty advisers were co-authors Stephen Williams and Michael Urynowicz, and she

From left, University of Wyoming M.S. student Lauren Connell, co-author Linda van Diepen, and UW Assistant Professor John Derek Scasta conduct ponderosa pine seedling surveys September 30, 2016, at one of the restoration study plots at RRS. (Photo by Elizabeth Traver)

was also mentored by former UW Professor Patricia Colberg, who is now department chair, professor, and National Academy of Education fellow at the University of Idaho's Department of Civil and Environmental Engineering.

Wilkin was awarded a master's degree in environmental engineering at UW in 2014. This effort led to the publication of: Wilkin, C. D., Soil amendments and microbial community recovery following high intensity forest fire [Master's thesis]: Laramie, Wyoming, University of Wyoming, 81 p.

Wilkin earned a bachelor's of engineering degree in bioresource engineering from McGill University, Montreal, Quebec, Canada, in 2010. In summer 2010, she was a research assistant at Brace Centre for Water Resources Management, McGill University, and in summer 2011 was farm co-manager of The Sharing Farm Society in Richmond, British Columbia, Canada.

In 2011, she moved to Laramie, where she began work on her M.S. degree. During her time at UW, she was a teaching assistant in soil mechanics, was a lecturer in the Department of Ecosystem Science and Management, participated in the study abroad program, and enjoyed competing in triathlons.

After earning her M.S., she was hired by WSP | Parsons Brinckerhoff, a global engineering and professional services firm that has since become WSP. Initially based in San Francisco, California, Wilkin was later transferred to WSP's environmental division in San Jose, California.

Wilkin says she enjoys solving problems where innovative solutions are applied to complex environmental challenges. Her duties with WSP include project management, technical oversight, and regulatory reporting on work involving site characterization, remedial investigation, and implementation, as well as water treatment system permitting and operations.

"I am interested in opportunities to contribute to groundwater and surface water management for urban and watershed-scale problems," Wilkin says. "I would say that my most interesting work involves groundwater—well drilling, injections, monitoring, pumping, and treating, anything that lets me see the subsurface!"

Among the projects she's worked on is the testing of soils for chemicals surrounding a lead-smelting plant in the Los Angeles, California, area. "We collected hand-augered soil samples, and then did a lot of sieving, characterizing, and analyzing of the samples," she says. "It's been fun to talk incessantly about soil science with my peers!"

LINDA T.A. VAN DIEPEN

Linda van Diepen, along with several graduate and undergraduate students she has and is mentoring, began conducting vegetation- and soils-related studies at the Rogers Research Site (RRS) shortly after coming to the University of Wyoming in 2015.

"I was fortunate to inherit the post-fire restoration experiment set up at RRS by Dr. Steve Williams and others (detailed in RRS Bulletin 5)," van Diepen says. "RRS is a great site for conducting post-fire ecosystem recovery studies, and in addition to the ongoing vegetation and soils measurements, the site offers a great opportunity to do many other studies, including wildlife responses to fire, grazing potential, forest management, entomology, and others."

Van Diepen joined the faculty in the UW Department of Ecosystem Science and Management as an assistant professor. Her research focus is ecosystem ecology, with an emphasis on the role of the microbial community in biogeochemical processes such as nutrient and carbon cycling.

"I am interested in understanding the responses of an ecosystem to various disturbances and how soil processes and plant-microbe interactions mutually control these ecosystem responses," van Diepen says.

She earned B.S. (1999) and M.S. (2002) degrees in environmental science in The Netherlands, and a Ph.D. (2008) in forest science at Michigan Technological University, Houghton, Michigan.

From 2009 to 2010, van Diepen was a postdoctoral fellow at the University of Michigan, Ann Arbor, Michigan. She then worked as a postdoc and later as a research scientist at the University of New Hampshire, Durham, New Hampshire, where she studied fungal ecology.

She has co-authored more than 20 peer-reviewed publications and co-presented over 40 abstracts and posters at scientific meetings across the country.

LARRY C. MUNN

Larry Munn is a professor emeritus of soil science in the University of Wyoming's Department of Ecosystem Science and Management. He started as an assistant professor at UW in 1981, and was promoted to associate professor in 1986 and professor in 1992. Munn began conducting soil studies at the Rogers Research Site (RRS) in 2009, and that work continued after the 2012 Arapaho Fire. Since retiring in 2014, he completed his writing and soils mapping work for Bulletin 6 (soils of RRS), and he since became involved in the work on this bulletin and the upcoming RRS Bulletin 8, which details a post-fire soil amendment and microbial community recovery study.

While at UW, Munn focused his research across Wyoming on soil genesis, morphology, and classification; soil–native plant community relationships; mine land reclamation; and the effects of coal-bed methane development on soils and landscapes. Munn taught a number of soils-related undergraduate and graduate classes at UW, and also led special-topic courses focused on the research of soil–geology–plant relationships in native, agricultural, and drastically disturbed ecosystems.

He received the John P. Ellbogen Meritorious Classroom Teaching Award in 1993 and was named the UW College of Agriculture's "Outstanding Teacher" in 1999.

After serving his country in the Vietnam War, Munn earned a B.S. in agronomy (emphasis on soils) in 1972 from The Ohio State University, an M.S. in natural resources (forest soils) from OSU in 1974, and a Ph.D. in crop and soil science (range soils) from Montana State University in 1977. Since joining the faculty at UW, Munn served on the western regional coordinating committee of the National Cooperative Soil Survey (NCSS), including two years as committee chair; the soil taxonomy and soil interpretations committees of the NCSS; and the soils and geomorphology committee of the American Society of Agronomy.

Munn retired on a small-acreage near Laramie, where he and his wife, Mary Lynne, enjoy raising an assortment of animals including horses, dogs, and chickens. He is a member of the Board of Supervisors of the Laramie Rivers Conservation District, one of 34 conservation districts across Wyoming.

University of Wyoming Professor Emeritus Larry Munn conducts soils-related research in southeast Wyoming's Snowy Range in August 2014.

MICHAEL A. URYNOWICZ

Michael Urynowicz is a professor of environmental engineering in the University of Wyoming's Department of Civil and Architectural Engineering. He has been involved in a wide range of research; however, of particular interest are field studies like the work performed at the Rogers Research Site. "These types of projects afford students and faculty alike with exceptional opportunities to better understand the complexities of natural systems through controlled experimentation."

Since joining the faculty at UW in 2002, Urynowicz has advised more than 15 M.S. and Ph.D. students, and has served on the research committees of more than 20 graduate students. He teaches a variety of undergraduate and graduate classes, including environmental engineering microbiology, solid waste engineering, hazardous waste site remediation, and engineering economics.

Professor Urynowicz is the director of the Center for Biogenic Natural Gas Research within the UW School of Energy Resources (http://www.uwyo.edu/urynowicz/biogenic_

Michael Urynowicz enjoys a trekking adventure to the Annapurna Himalayas of north-central Nepal in 2006. The prominent mountain in the background is Machhapuchhre, elevation 22,943 ft (6,993 m). Also spelled Machapuchare, the mountain is considered sacred and is closed to climbers.

natural_gas.html), and he is faculty co-adviser of the UW Chapter of Engineers Without Borders (https://uwyo.campuslabs.com/engage/organization/ewb).

He earned a B.S. in chemical engineering at Michigan State University in 1990, an M.S. in civil and environmental engineering at the University of Wisconsin in 1995, and master's and doctorate degrees in environmental science and engineering at the Colorado School of Mines in 1998 and 2000.

Urynowicz was hired as an assistant professor at UW in 2002. He was promoted to associate professor in 2008 and professor in 2014.

ROBERT W. WAGGENER

Rogers Research Site (RRS) bulletin project manager Robert Waggener calls his work on the RRS publication series one of the most rewarding challenges of his career. It has combined his interests in agriculture, natural resources, and the great outdoors with his experience in editing, writing, background research, photography, and project management.

Among the many reasons why Wyoming native Robert Waggener remains in his home state is scenes like this—the great Titcomb Basin from high up on Fremont Peak in the rugged Wind River Range. Waggener climbed the peak, elevation 13,751 ft (4,191 m) with his hiking buddy and brother, John Waggener, an archivist at UW's American Heritage Center.

But what Waggener has enjoyed most about the project is his collaboration with more than 100 people who have contributed to the bulletins thus far. They have included former and current University of Wyoming students, faculty, and staff; state and federal wildlife, lands, and forestry managers; Laramie Peak residents who are familiar with RRS and surrounding lands; and people who became friends with Colonel William C. Rogers, who retired on his forested property in the remote north Laramie Mountains after serving his country with distinction in the U.S. Army.

It's Waggener's hope that the RRS bulletin series will not only showcase the past and current research that is taking place at the site, but that they will inspire future students, both undergraduate and graduate, to work with faculty mentors and others on projects that will benefit the many resources this mountain range has to offer, including a variety of habitats that support a myriad of plant and wildlife species.

Waggener earned a B.S. in journalism from UW in 1983, and then worked at The Sheridan Press as a reporter, Buffalo Bulletin as managing editor, UW College of Agriculture and Natural Resources/UW Extension as editor, and Wyoming State Geological Survey as editor-in-chief.

Waggener launched his full-time freelance writing, editing, and photography career in 2010, focusing on agriculture and natural resources in Wyoming and the West. Among his clients are the Wyoming Agricultural Experiment Station, which manages RRS; Rocky Mountain Geology Journal, published by the UW Department of Geology and Geophysics; Western Farmer-Stockman magazine; and Progressive Farmer magazine.

STANDING ON THE COLONEL'S SHOULDERS

The human soul needs actual beauty more than bread

By Robert Waggener

> *"The human soul needs actual beauty more than bread."*

This quote by English poet and novelist D. H. Lawrence characterizes Colonel William Catesby Rogers' retirement years as the multi-millionaire focused on emotional well-being, exuberance, free-thinking, and spontaneity instead of materialism and prosaic pursuits. Friendships—whether with local ranchers and school teachers or hippies and monks from far away—meant much more to Colonel Rogers than a trophy home, lavish furniture, and expensive cars. He lived in a one-room cabin, drove a Bronco, wore hand-me down clothing, and scrounged for old dishes and canning jars in southeast Wyoming's Laramie Mountains. This is where he spent most of his retirement years, working the small piece of land he purchased several years after his honorable discharge from the U.S. Army in 1962. In those isolated, rugged hills, he also enriched his life by reading, writing, and conversing with friends and strangers alike.

Among his frequent visitors were Casper school teacher Levida Hileman and her daughter, Colleen Hogan, who spent part of each summer on The Colonel's 320-acre Triple R Ranch near the prominent Laramie Peak. Their friend, William Rogers, lived a most frugal life, and so it came as a complete surprise to learn after he died in 2003 at age 96 that he was worth a lot of money. "Oh, yes, I have another funny story about Bill," says Colleen, as she reminisces about the eccentric gentleman who became an important figure

Colonel William Catesby Rogers enjoyed his beloved Triple R Ranch in the Laramie Mountains of Wyoming after retiring from the U.S. Army. Colonel Rogers, who would have been about 80 when this photo was taken in the mid-1980s, willed the land to the University of Wyoming, which renamed the property the Rogers Research Site in his honor. He also willed millions of dollars to institutions, including UW, along with charitable organizations, missions, monks, friends, students, and others. (Photo by Colleen Hogan; from RRS Bulletin 4)

Colonel William C. Rogers, along with his hired hand, friends, and guests, stayed in rustic cabins on his retirement property in the Laramie Mountains. The Colonel, as he was known by friends, lived a very frugal lifestyle, spending little on upgrading the cabins and outbuildings. The structures, including this one, known informally as The Original House, were destroyed during the 2012 Arapaho Fire. (Photo by Colleen Hogan)

in her life, a mixture of motivating father and mentoring grandfather. "Bill would go to F.E. Warren Air Force Base in Cheyenne to get a haircut. They would charge $5, and you could tell that Bill didn't like spending that kind of money on a haircut. Well, one summer he had it in his head that I should cut his hair. I tried to tell him, 'Bill, I don't cut hair.' He responded, 'Oh, you'll be just fine. Go right ahead.'"

The Colonel gave Colleen an old pair of scissors and a comb, and the first two haircuts went just fine. "I told him how beautiful his hair was. It was very beautiful—thick and white and very beautiful for a man his age. Yea, he said he felt quite lucky to have a head full of hair," remembers Colleen, who, like other guests, had to do chores around The Colonel's property in exchange for a rustic vacation amongst historic cabins needing attention, towering ponderosa pines, including one sporting a basketball hoop without a net, and dainty wildflowers growing between granite rocks. That meant tending the vegetable garden, picking weeds, collecting cow patties for the compost pile, pruning trees, working on dilapidated structures, and, yes, providing the occasional haircut.

During one trip to town, Colonel Rogers bought a used pair of clippers, thinking that would lead to not only a better cut, but one that wouldn't take nearly as long as the comb-and-scissor trim. "I had never used clippers before and ended up giving him a very patchy haircut—to the scalp in some places, longer in other places," Colleen says. "He didn't have me cut his hair again. He figured it was worth his $5 and gas to go to Warren Air Force Base to have his hair cut."

Adds Colleen, with a laugh, "I haven't used clippers since."

Levida, who retired in Cheyenne with her husband, Brock Hileman, remembers the story like it was yesterday. "Those old clippers didn't have a guide on them, and Colleen had never done anything like that. Bill had a beautiful, thick head of hair, very beautiful white hair, and when Colleen was done with that haircut he came out pretty funny looking." After pausing for a moment, Levida quietly resumes her reflections, talking about the positive influence Colonel Rogers had on many people, including her daughter, now a health facility surveyor for the Wyoming Department of Health. “The Colonel was very fond of Colleen. I always think he looked at her as kind of a daughter or granddaughter. When she turned 16, he gave her a book about makeup. I think that book was from the 1950s and I’m sure he bought it used somewhere, but it was a very nice gesture. It came from his heart.”

That old book and old pair of clippers, too, exemplified how Colonel Rogers lived his life, despite having a vast fortune, in part by actively buying stocks in promising companies. George Portwood, who managed the nearby Double Four Ranch and also served as the Laramie Peak Fire Zone warden for nearly two decades before retiring in the 2000s, says he got to know The Colonel while fighting brush fires in the area. “When there’s a fire in this country you see a lot of neighbors pulling together to help, and Colonel Rogers was one of them. He was getting pretty elderly by then, but you would still see him out there scratching around trying to help put out a fire. If a fire is in your backyard, you go help fight it.”

As manager of the Double Four, Mr. Portwood oversaw a large cattle operation, and in the late 1970s Colonel Rogers showed up at a branding. At the time, he would have been in his early 70s. “He didn’t wrestle any calves, but he helped the best he could. Mostly, he enjoyed visiting with the people. I know that he really enjoyed the branding.” Portwood says he regrets not getting to know The Colonel better, believing at the time he was a pretty private man. But he learned a lot about Bill through casual conversations and by the way he lived. “He was certainly an eccentric feller, definitely not a westerner. I heard that he came from back East, and I know that he traveled

Guests of Colonel William C. Rogers enjoyed a wide range of activities on his Triple R Ranch, including basketball. An old hoop purchased at a garage sale by Levida Hileman was nailed to a ponderosa pine, and dirt covered with pine needles provided the playing surface. At the time, Levida’s daughter, Colleen Hogan, was in grade school basketball. Miraculously, the tree and hoop survived the 2012 Arapaho Fire, which destroyed virtually everything on the property. Also surviving the fire was an old sheep wagon (pictured on Page 5), which was willed to Colleen and Levida and is still being used today. (Photo by Colleen Hogan) the world. He had a mind of his own, and he was pretty set in his ways."

Like others, Portwood was surprised to learn that Colonel Rogers was a man of wealth. "He lived a pretty lean life up in this country; that's just the way he was. You could tell by that tiny cabin he lived in. He pretty much lived more or less like a hermit. It was like he wanted to get away from it all."

The Colonel certainly wanted to get away from it all after retiring from the military, and that's one of the reasons he bought the secluded piece of land. But he certainly did not want to get away from people. Levida Hileman recalls: "We appreciated being up there in those beautiful mountains with Bill. Oh, I need to tell you another funny story. The Colonel knew where all the old mountain dumps were, and we would go out with him looking for old canning jars. In that old cabin of his, I knew he couldn't sterilize those jars very well, but he would still use them for canning."

On several occasions, Bill shared some of his canned fruit with Levida and Colleen. They would politely thank him, and then find a way to secretly discard the pears and peaches in the compost pile or garden. It became clear to those who became friends with Bill during his retirement that his soul needed beauty more than bread, and beauty came each day as he enjoyed campfire dinners with friends from near and far. During one such occasion, The Colonel said he would furnish steaks and beer as long as Levida agreed to do the cooking. "That sounded OK with me, so I told The Colonel that I would grill the meat over a fire. He arrived with a package of pork steaks, and when I opened the package those chops were all blue and slimy," she says with a laugh. "When The Colonel stepped away, I whispered to Colleen, 'Take these pork chops and bury them somewhere. Get them far enough away so that our dog won't smell them.'"

When Bill arrived back at the campfire, Levida remembers, "I had to be honest with him. I told him that the pork chops weren't looking too good so I got rid of all but one. I then asked him, 'Would you rather have that pork chop or some nice chicken that I cooked?' 'Oh, I'll have some of that chicken,' he responded."

Levida adds with a smile: "You've made me feel real good talking about The Colonel because he was so special to us, very special. He traveled to many places, and in those travels he met many people whom he invited to his property in the Laramie Mountains. There were hippie types and poets. Once he invited some Zapotec weavers up there. He was a very eccentric, unique person. Above all, he loved his place in the mountains, and he wanted others to enjoy it with him."

A variety of wildflowers and other plants grow in the rocky soils at the Rogers Research Site. (Photo by Mollie Herget)

PRE- AND POST-FIRE SOIL COMPARISONS, ROGERS RESEARCH SITE, NORTH LARAMIE MOUNTAINS, WYOMING

By Stephen E. Williams,[1–2] *Claire D. Wilkin,*[3] *Linda T.A. van Diepen,*[4] *Larry C. Munn,*[5] *Michael A. Urynowicz,*[6] *and Robert W. Waggener*[7]

KEY WORDS
actinomycetes, Arapaho Fire, arbuscular mycorrhizal fungi, bacteria, ectomycorrhizal fungi, fire ecology, fungi, high-severity wildfire, Laramie Mountains, phospholipid fatty acids, ponderosa pine (*Pinus ponderosa*), pre- and post-fire soil comparisons, protozoa, Rogers Research Site, soil microbial community, soil nutrients, University of Wyoming, wildfire, Wyoming Agricultural Experiment Station

INTRODUCTION

Soil microbiological and chemical properties change under the influence of fire. These changes vary significantly based on the severity and intensity of the fire, site location, and micro- and macro-topographic and climatic variations (Certini, 2005). Soil property effects can include soil carbon (C) content, pH, electrical conductivity (EC), and the concentrations of major cations and anions including nitrate (NO_3^-), ammonium (NH_4^+), phosphate (PO_4^{3-}), calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na). Changes in the soil nutrient content together with changes in microbial community composition in response to fire may alter re-vegetation, decomposition, and overall recovery.

On June 27, 2012, lightning started the Arapaho Fire in southeast Wyoming's Laramie Mountains near the prominent Laramie Peak (InciWeb, 2012). The fire burned approximately 98,000 acres (39,700 hectares) of wildland before being contained in late August (Fig. 1). Among the areas it burned was the University of Wyoming-owned Rogers Research Site (RRS). This site is managed by the Wyoming Agricultural Experiment Station through the James C. Hageman Sustainable Agriculture Research and Extension Center (SAREC) near Lingle, Wyoming. On July 2 and 3, the fire swept through RRS, which became a heterogeneous

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[1] For specific questions about this report (along with general questions about RRS research, information about access, driving directions to RRS, access to high-resolution digital copies of the bulletin, etc.) please contact the James C. Hageman Sustainable Agriculture Research and Extension Center (SAREC) at sarec@uwyo.edu; 307-837-2000; or 2753 State Highway 157, Lingle, WY 82223-8543.

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[3] Environmental consultant with WSP, San Jose, California. At the time of this research, Wilkin was a graduate student at the University of Wyoming. Wilkin, who was co-advised by Professors Stephen Williams and Michael Urynowicz, earned a master's degree in environmental engineering in 2014.

[4] Assistant professor of soil microbial ecology, UW Department of Ecosystem Science and Management.

[5] Professor emeritus of soil science, UW Department of Ecosystem Science and Management, Laramie, Wyoming.

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Figure 1. The lightning-caused Arapaho Fire started in the north Laramie Mountains on June 27, 2012, during a severe drought. The high-intensity fire, which swept across RRS property on July 2 and 3, would burn approximately 98,000 ac (39,700 ha) of public and private lands before being contained in late August. This photo shows the Arapaho Fire blowing up one day after starting. (Photo by Josh McGee)

Figure 2. The high-intensity Arapaho Fire killed the majority of vegetation on RRS and surrounding lands, including thick-barked ponderosa pine (*Pinus ponderosa*). This photo was taken in September 2013, approximately 14 months after the fire. (Photo by Steve Williams)

patchwork of mostly standing dead ponderosa pine (*Pinus ponderosa*),[8] standing burned quaking aspen (*Populus tremuloides*),[9] bare soil, and rock (Figs. 2–3), though a few pine trees and some stands of aspen did survive (Williams and Waggener, 2017a). Across the 320-ac (~129.5-ha) site was evidence of varying degrees of burn severity and intensity. There were trees with charred trunks and a full crown of crisp brown needles, while

Figure 3. Based on the color of soils in some areas, temperatures of the high-intensity Arapaho Fire reached upwards of 900°F (500°C). (Photo by S. Williams)

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[8] Ponderosa pine, with its thick bark, has evolved to survive frequent, low-intensity ground fires; however, the 2012 Arapaho Fire burned with such intensity that the majority of ponderosa pine (even mature trees more than 150 years old) were killed across the approximate 98,000-ac (~39,700-ha) burn area. Little natural regeneration had been observed as of fall 2017, a full five years after the fire (Herget et al., 2018).

[9] The aboveground quaking aspen burned at RRS and across much of the 2012 Arapaho Fire area, but the aspen forest remains living belowground. Five years following the fire, there was fairly good aspen regeneration occurring in some areas of the fire (Herget et al., 2018).

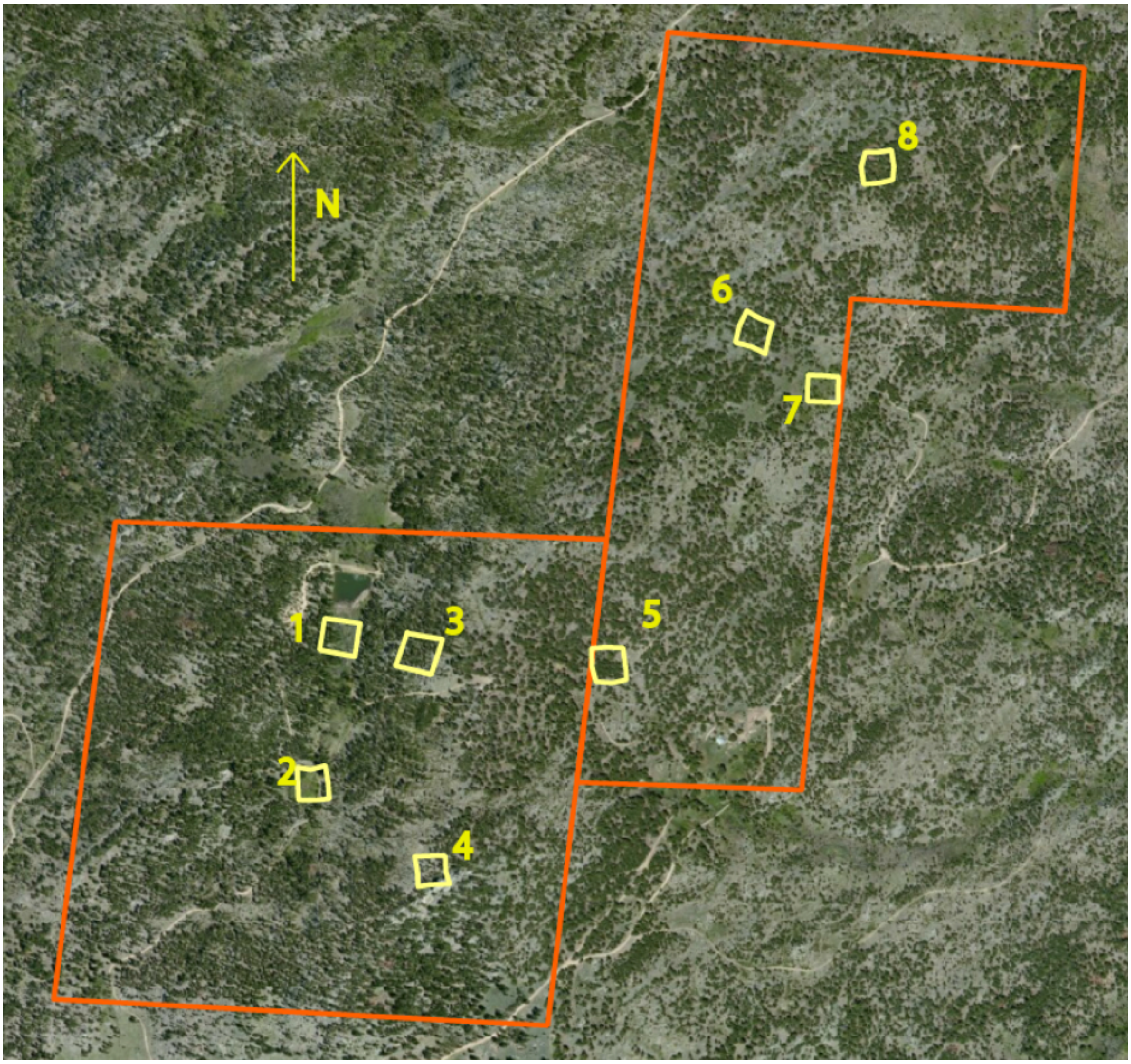
whole areas of forest were completely devoid of needles or fine twigs. The former indicates a low-intensity ground fire, while the latter indicates a full crown fire and complete combustion of surface organic matter (Neary et al., 1999). Our assessment was that depending on the location, the Arapaho Fire effectively burned the RRS between moderate- and high-intensity, with temperatures estimated to have reached nearly 900°F (500°C) based on the colors of the soils in some areas (Williams and Waggener, 2017a). Using eight 50-m by 50-m (164-ft × 164-ft) monitoring plots established prior to the fire as sample sites (Fig. 4), we compared soil chemical and microbiological properties to examine preliminary ecological impacts of this burn.

ORIGINAL STUDY: CHARACTERIZATION OF THE RRS

Fortuitously, eight monitoring plots (Fig. 4) had been established in spring 2012—just weeks prior to the fire—as part of our original study. This study was to document the resources of RRS including soils, plant distribution, water sources, topographic features, and belowground biota. In addition, planning efforts were underway to determine sources and levels of biologically available nitrogen (N) at RRS.

Our original study, aside from describing the RRS physically, chemically, and biologically, was to develop an N budget for the site and to determine whether certain nutrients—probably N and perhaps phosphorus (P)—were limiting the growth of

Figure 4. Aerial view of RRS boundary and locations of eight plots where soils were sampled. This image was taken in 2012, shortly before the Arapaho Fire burned through RRS and surrounding lands. Plot 1 is riparian vegetation, Plots 2 and 7 are in aspen groves, Plots 3 and 8 are dense ponderosa pine, Plot 4 is a rocky outcrop area with open ponderosa pine, and Plots 5 and 6 are open ponderosa pine. (Aerial image from National Agriculture Imagery Program [NAIP]; overlay mapping by Claire Wilkin)



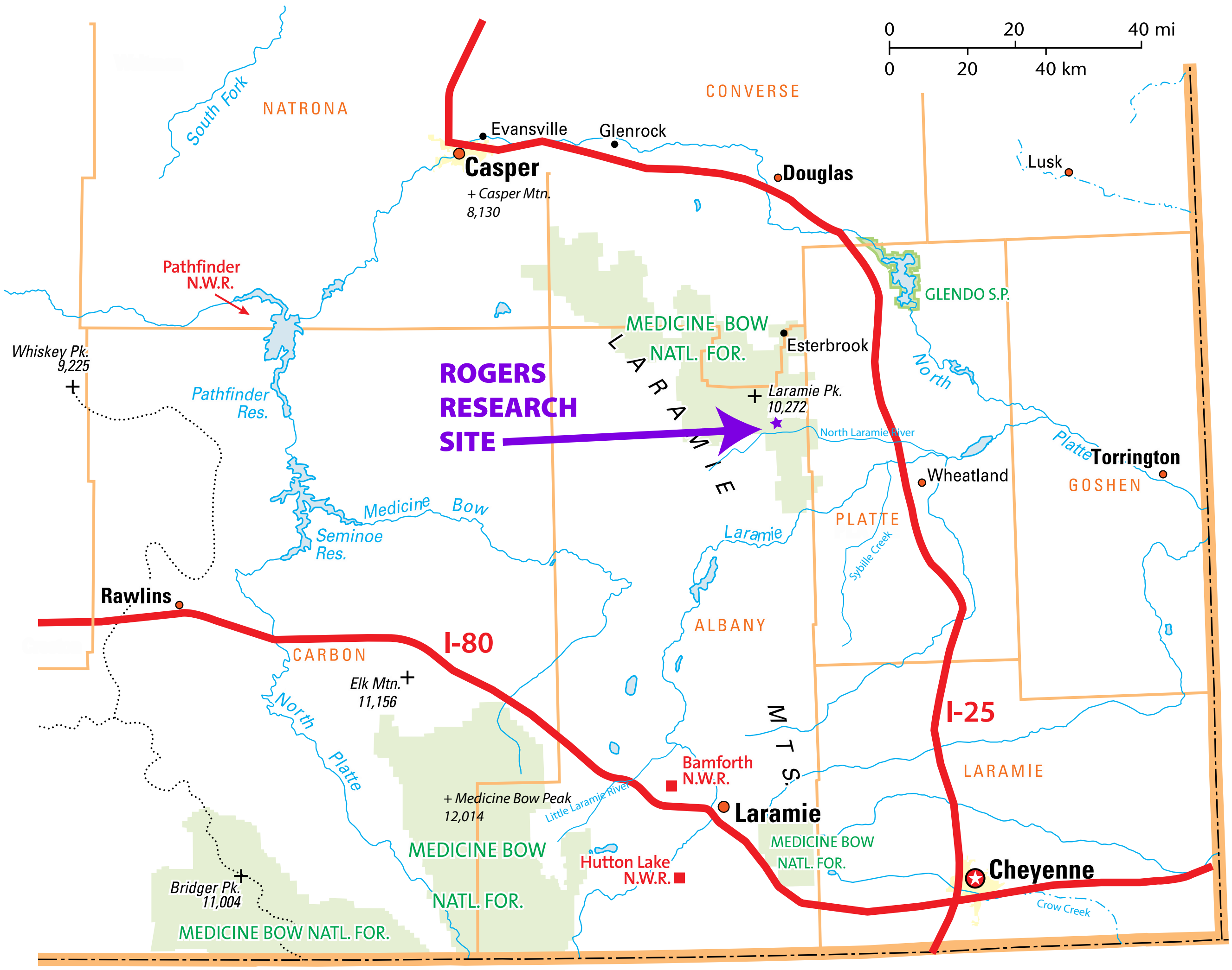


Figure 5. Rogers Research Site is located in the north Laramie Mountains approximately 5 mi (~8 km) southeast of Laramie Peak and 25 mi (40 km) northwest of Wheatland, Wyoming. (Map by Tanya Engel, from Williams and Waggener, 2017b)

Figure 6. The high-intensity Arapaho Fire, which burned in the area of the prominent Laramie Peak in the north Laramie Mountains, killed the majority of thick-barked ponderosa pine, which has evolved to survive frequent, low-intensity fires. This photo was taken in July 2015, three years after the fire. (Photo by Michael Curran)

the forest species on the site. We investigated the N budget in an effort to answer the question: where was N coming from in this forested ecosystem? We observed numerous plants at RRS that were capable of fixing N. These included various legumes, including lupines (*Lupinus* spp.), locoweeds (*Astragalus* spp.), and clovers (*Trifolium* spp.). Other N-fixing plants included several non-leguminous shrubs and small trees—alder (*Alnus* spp.) was found along wet drainages, while antelope bitterbrush (*Purshia tridentata* [Pursh]) and two species of buckbrush (*Ceanothus* spp.) occurred in the uplands.

WILDFIRE CHANGES HYPOTHESIS

Because the 2012 Arapaho Fire greatly affected our original study, our new hypothesis was that important nutrients in the surface soil would be available in higher concentrations following this moderate- to high-intensity burn and that pH and EC would reflect this. These important nutrients would include previously biomass-bound K, Ca, Mg, P, and N. Responding to this flush in nutrients, we also expected that the abundance and community structure of the surface soil microbial biomass would be significantly changed. Fire modifies ecosystems very quickly, allowing some organisms that have been dormant to become active and others to decrease or disappear. As such, understanding how fire impacts these organisms is paramount to understanding the ponderosa pine system at RRS and surrounding lands.

STUDY AREA

Rogers Research Site (RRS) is located in the north Laramie Mountains approximately 5 mi (~8 km) southeast of Laramie Peak and 25 mi (40 km) northwest of Wheatland, Wyoming (Figs. 5–6; Waggener, 2017; Williams and Waggener, 2017a). Before the fire, ponderosa pine and other vegetation covered much of RRS (Fig. 7) and lands in the vicinity (Williams and Waggener, 2017a). In 2006, a vegetation mapping project of RRS and lands immediately surrounding the site using high spatial resolution AEROcam

Figure 7. Prior to the 2012 Arapaho Fire, the majority of lands in the north Laramie Mountains, including the RRS property, were covered with ponderosa pine in various age classes. This photo shows the small reservoir that Colonel William C. Rogers, with the help of others, constructed on his land. It is fed by spring water and natural precipitation. The photo was taken on June 12, 2012, three weeks before the lightning-caused Arapaho Fire burned across RRS. (Photo by Jim Freeburn)

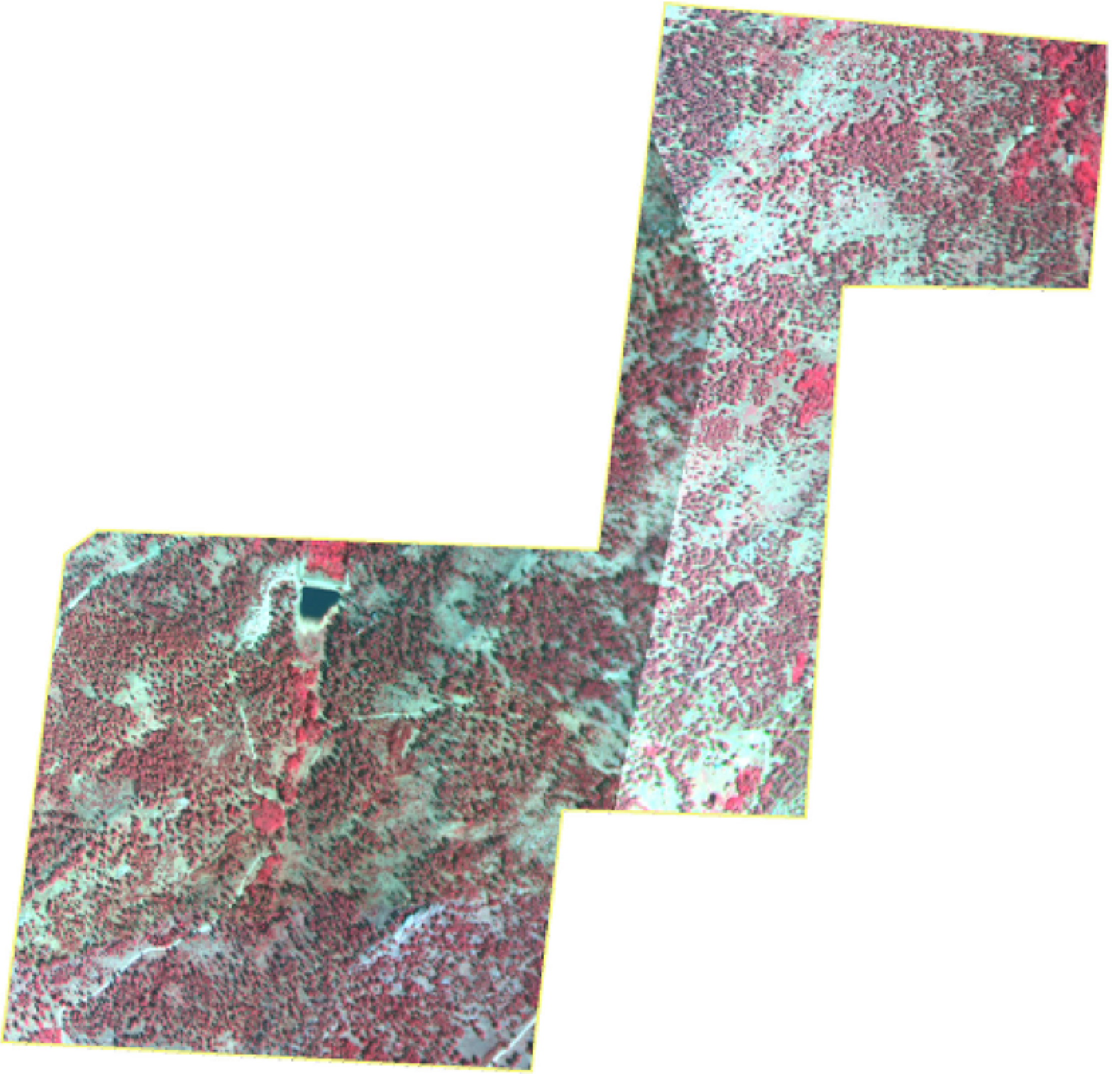


Figure 8. AEROcam photo of the Rogers Research Site in summer 2006, approximately six years before the Arapaho Fire. Shades of red indicate live vegetation. (Image by Upper Midwest Aerospace Consortium, courtesy of Wyoming Geographic Information Science Center [WyGISC])

Figure 9. Prior to the 2012 Arapaho Fire, ponderosa pine in various age classes and densities covered the majority of RRS and surrounding lands. This photo was taken in June 2007. (Photo by S. Williams, from Seymour et al., 2017)

photography (Airborne Environmental Research Observational Camera[10]), heads-up digitizing, and ground-truthing determined that RRS was predominately ponderosa pine forest (80% [Figs. 7–9]) (Seymour et al., 2017). The remainder of the site was mixed grass and shrub lands (10% [Fig. 10]), quaking aspen (4% [Fig. 11]), and other features, including rock outcrops (Fig. 12), roads, a small reservoir (Fig. 7), and bare ground (6%) (Seymour et al., 2017). AEROcam photographs taken approximately two weeks after the fire revealed that only about 5% of previous living vegetation survived (Fig. 13).

A variety of vegetation and habitats at RRS and surrounding lands support numerous wildlife species, both resident and migratory. Among the resident species is the wild turkey (*Meleagris gallopavo* [Fig. 14]), while migratory bird species include the hairy woodpecker (*Picoides villosus* [Fig. 15]), northern saw-whet owl (*Aegolius acadicus*), and turkey vulture (*Cathartes aura* [Fig. 16]).

SOILS OF THE RRS

Four of the 12 orders of soil are present at RRS: Alfisols, Entisols, Mollisols, and Inceptisols (Munn et al., 2018). Soils on forested slopes are moderately developed Alfisols and shallow Entisols with low inherent fertility and low water-holding capacity due to coarse texture. They are developed from granitic substrate. Mollisols are found under herbaceous vegetation cover along streams and in areas of springs and under dense aspen stands. These soils are deeper, finer textured, and contain more organic matter. Inceptisols were not mapped because of their small areal extent (Munn et al., 2018). The representative soils for mapping units at RRS are classified as the following four series: Alderon, Cathedral, Dalecreek, and Kovich (Fig. 17; see Munn et al., 2018, for descriptions of each). Figures 18–20 show fairly well-developed soil profiles at RRS. The top horizon is made up almost entirely of organic debris and partially

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[10] The former Airborne Environmental Research Observational Camera (AEROCam) was an aerial photography system owned by the University of North Dakota. It was available for use by members of the Upper Midwest Aerospace Consortium (UMAC), including Wyoming and other states, and was designed to take high spatial resolution photographs in the visible and near-infrared wavelengths. Such imagery is often used for vegetation analysis, an important tool in precision agriculture and natural resource management, and to aid in the rapid response to disasters (Seymour et al., 2017).

Figure 10. Among the common shrub species in the Laramie Mountains, including RRS and surrounding lands, is antelope bitterbrush (*Purshia tridentata*). (Photo by Dorothy Tuthill, from Seymour et al., 2017).

Figure 11. Among the common deciduous trees occupying wetter habitats in the Laramie Mountains, including RRS and surrounding lands, is quaking aspen (*Populus tremuloides*). In the tree is a northern saw-whet owl (*Aegolius acadicus*), an uncommon visitor to Wyoming. This photo was taken prior to the Arapaho Fire. (Photo by S. Williams, from Seymour et al., 2017)

Figure 12. Granite rock outcrops are common in the Laramie Mountains, including RRS and surrounding lands. This photo was taken in August 2014, just over two years following the Arapaho Fire. (Photo by Larry Munn)

Figure 13. AEROcam photo of RRS on July 18, 2012, approximately two weeks after the Arapaho Fire burned across the site. Shades of red indicate live vegetation. Only approximately 5% of vegetation survived the fire at RRS. (Image by Upper Midwest Aerospace Consortium, courtesy WyGISC)

Figure 14. Among the resident bird species of the north Laramie Mountains is the wild turkey (*Meleagris gallopavo*). Here, a wild turkey makes its way through a thick stand of forbs and grasses that established following the Arapaho Fire. This photo was taken in August 2014, slightly more than two years after the fire. (Photo by L. Munn)

Figure 15. Among the migratory bird species that inhabits the north Laramie Mountains is the hairy woodpecker (*Picoides villosus*), shown here feeding on insects in a dead ponderosa pine tree at RRS. A catastrophe for one set of species presents an opportunity for another. This photo was taken on August 14, 2014, slightly more than two years after the Arapaho Fire. A variety of forbs and native grasses established after the fire, but so did weeds, including dense stands of Canada thistle (*Cirsium arvense*), shown here going to seed in the foreground and background (Photo by L. Munn)

Figure 16. Another migratory bird species inhabiting the north Laramie Mountains is the turkey vulture (*Cathartes aura*), here pictured on September 24, 2013, soaring above RRS. (Photo by S. Williams)

decomposed organic materials. It extends from the surface to about 4 cm (~1.5 in) and is called the O horizon. The second horizon, or A horizon, is a mineral soil horizon, but also contains considerable organic C and extends from about 4 to 11 cm (~1.5–4.5 in). The third horizon, or B horizon, is a horizon of accumulated clay, and it extends from about 11 to 17 cm (~4.5–7 in). From 17 cm (7 in) and deeper is the C horizon, usually described as the parent material of the soil; here, the parent material is a sandy substrate (see Munn et al., 2018, for a detailed discussion about the soils of RRS).

METHODS

To test our original hypotheses, soil samples were collected from a soil pit excavated at the center of each square plot (Fig. 21; Wilkin, 2014). Fortuitously, this work occurred in June 2012, just days and weeks before the lightning-caused Arapaho Fire started on June 27 (it burned across RRS on July 2 and 3). To address fire effects, additional soil samples were collected in late July 2012 (Fig. 22), shortly after the area was deemed 'safe' to enter. Most of the pre- and post-fire soil sampling was done by co-authors Williams, Wilkin, and Munn, with the assistance of UW graduate student Michael Curran (Fig. 21), but undergraduate students in a soils class taught by Williams also helped collect samples (Cover; Fig. 22). Samples were taken post-fire from a small pit excavated within 0.5 to 1.0 m (~1.6 to 3.3 ft) from the pre-fire sampling sites. During sampling of these soils, horizons were designated and samples were taken from each distinct depth. A subsample of each horizon sample was placed on dry ice. From these subsamples, nitrate (NO_3^-) and ammonium (NH_4^+) were extracted using 2M KCl (2-molar potassium chloride) and analyzed using BioTek™ colorimetric assays based on methods described in Doane and Horwáth (2003). Another frozen subsample was freeze-dried and used for estimation of total microbial biomass and community composition by phospholipid fatty acid analysis (PLFA).

The PLFA method allows researchers to identify the presence and quantity of fatty acid chains known to occur in the cellular membranes of certain microbial groups (Frostegård et al., 1991). Some fatty acids are observed almost exclusively in one group of organisms—*18:2ω6c*. Fatty acid nomenclature refers to the number of C atoms in a chain—in this case 18—and the type and location of double bonds, here with two (2) cis double bonds, the first of which is six (6) C atoms from the methyl end. The *18:2ω6c* fatty acid is synthesized largely by fungi (Frostegård et al., 2011); therefore, its measured value is utilized to estimate the quantities of fungi in various soil-testing scenarios. The signatures used to calculate abundance of each microbial group are listed in Table 1.

Using refrigerated (4°C [39°F]) soil samples, pH and electrical conductivity (EC) were measured in a 1:2 ratio of soil:deionized water mixture, using a pH and EC meter

Table 1. List of fatty acid signatures used to describe soil microbial communities.

	Fatty Acids Used for Each Category					
Total Microbial Abundance	Sum of all signatures used					
Bacteria	14:0 iso	15:0 iso	15:0 anteiso	16:0 iso	16:1 w7c	17:0 anteiso
	17:0 cyclo	18:1 w9c	18:1 w7c			
Actinomycetes	16:0 10-methyl	17:0 10-methyl	18:0 10-methyl			
Arbuscular mycorrhizal fungi	16:1 w5c	20:1 w9c				
Fungi	18:2 w6c					
Protozoa	20:4 w6c					
Fungal Signatures/ Bacterial Signatures	Fungal Signatures/Bacterial Signatures					

combination probe. Soil cations from a saturated paste were analyzed at the Wyoming Soil Testing Laboratory[11] in 2012 using inductively coupled plasma–mass spectrometry (ICP–MS). Phosphate (PO_4^{3-}) extracted by the Melich No. 3 method was also measured. Both methods are described in detail by Gavlak et al. (2005).

Microbial community data, from the PLFA analysis, were compared using a paired *t*-test run in SAS® 9.2 analytic software (SAS Institute Inc., Cary, North Carolina). Samples taken below riparian and aspen sites were excluded from analysis to provide more appropriate comparison with a subsequent post-fire randomized complete block design (RCBD) study under ponderosa pine (see Herget et al., 2018). The rocky outcrop soils (site 4; Appendix A) were included due to the small—but dominant—presence of *P. ponderosa* on the site. To maintain analysis consistency with the treatment experimental design, samples only from surface soils (A horizon) were compared for PLFA. We tested averages for pre- and post-fire signatures of total microbial abundance, bacteria, actinomycetes, arbuscular mycorrhizal fungi (AMF), fungi, protozoa, and fungi-to-bacteria ratio. Due to the heterogeneity of horizon development and sample depth across sample sites, we grouped data points using more general surface horizon (A) and subsurface horizon (B) designation for all other chemical analyses (NO_3^-, NH_4^+, PO_4^{3-}, pH, EC, and cations).

RESULTS AND DISCUSSION

Post-fire soils were substantially richer in available base cations and phosphate, and surface horizon (A) properties were more severely altered as compared to the subsurface (B) horizon (Table 2; Appendix A). The pH of surface soils increased significantly (by 0.6 units, on average) across the eight sites sampled. Ca, Mg, K, EC, and PO_4^{3-} all increased significantly in the surface horizon following the fire, while Na decreased (Table 2; Appendix A). The organic horizon (O horizon) was consumed by the fire (Munn et al., 2018). Thus, the fact that the total N and C increased post-fire in the surface horizon may reflect the amount of partially combusted plant parts (e.g., needles, leaves, and twigs) that leached from organic layers post-fire and increased the levels of N and C in the surface mineral soil. In the surface horizons only, both NH_4^+ and NO_3^- increased significantly (Table 2; Appendix A). All fatty acid signatures demonstrated a post-fire reduction compared with pre-burn samples (Fig. 23). Across the five sites with ponderosa pine, significant differences (alpha <0.05) were observed for actinomycetes ($n = 5$; $t = -2.32$; $p = 0.0374$) and protozoans ($n = 5$; $t = -3.25$; $p = 0.0064$), while arbuscular mycorrhizal fungi (AMF) ($p = 0.094$; $t = -1.81$) and fungi ($p = 0.0937$; $t = -1.81$) showed significant differences at an alpha of 0.10 (Fig. 23).

In general, the fire increased availability of extractable phosphorus (P) and base-forming cations in surface soils, including calcium (Ca), magnesium (Mg), and potassium (K), but not in subsurface horizons. This is not surprising as soil heating and its effects do not tend to travel more than 5 cm (2 in) into the soil during a fire, depending on soil moisture content and burning time (Giovannini and Lucchesi, 1997; Neary et al., 1999). The increase in post-fire surface soil pH (Table 2; Appendix A) is generally explained by the (1) increase in cations that increase the pH; (2) combustion of organic acids; and (3) consumption of hydrogen ions (H+) (Hart et al., 2005). Inorganic N increased significantly for both ammonium and nitrate in surface soils, and ammonium increased overall. Percent N also increased overall. In general, the large spike in N in the post-fire soils is corroborated by observed rates of N mineralization in medium- to high-intensity burn soils in a study by

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[11] The University of Wyoming Soil Testing Laboratory discontinued analyzing soil samples for the public in late 2011, closing down permanently thereafter.

Table 2. Pre- and post-fire soils data from eight 50 m × 50 m (164 ft × 164 ft) plots at Rogers Research Site.

Variable	Horizon	Pre-fire	Post-fire
NO_3^- (mg/kg)	A (surface) *	8.77 (11.1)	27.96 (50.49)
	B (subsurface)	7.51 (6.20)	10.87 (14.67)
NH_4^+ (mg/kg)	A (surface) *	6.62 (4.12)	16.68 (9.97)
	B (subsurface)	7.39 (4.04)	5.09 (1.70)
pH	A (surface) *	6.05 (0.53)	6.60 (0.85)
	B (subsurface)	5.93 (0.35)	5.93 (0.44)
EC (µS/cm)	A (surface) *	0.26 (0.15)	0.95 (0.86)
	B (subsurface)	0.20 (0.10)	0.27 (0.13)
PO_4^{3-} (mg/kg)	A (surface) *	30.91 (14.93)	89.95 (71.53)
	B (subsurface)	18.86 (8.75)	25.56 (8.80)
SAR	A (surface) *	0.88 (0.37)	0.19 (0.12)
	B (subsurface) *	1.16 (0.32)	0.47 (0.16)
Ca (meq/L)	A (surface) *	1.47 (1.24)	8.16 (7.44)
	B (subsurface)	0.71 (0.77)	1.52 (0.34)
Mg (meq/L)	A (surface) *	0.57 (0.42)	3.50 (3.90)
	B (subsurface)	0.33 (0.24)	0.54 (0.11)
K (meq/L)	A (surface) *	0.28 (0.12)	0.90 (0.73)
	B (subsurface)	0.21 (0.11)	0.19 (0.05)
Na (meq/L)	A (surface) *	0.73 (0.21)	0.34 (0.15)
	B (subsurface) *	0.78 (0.18)	0.48 (0.20)
% N	A (surface) *	0.20 (0.11)	0.38 (0.28)
	B (subsurface)	0.07 (0.04)	0.16 (0.17)
% C	A (surface) *	3.38 (1.70)	5.75 (4.59)
	B (subsurface)	0.80 (0.43)	2.02 (2.36)
C:N	A (surface)	17.42 (3.57)	15.42 (3.55)
	B (subsurface)	12.14 (4.47)	13.24 (2.41)

Values represent the mean values for the eight plots with standard deviation in parentheses. NO_3^- (nitrate), NH_4^+ (ammonium), and PO_4^{3-} (phosphate) are in milligram/kilogram (mg/kg) dry soil. All cations are in milliequivalents per liter (meq/L), a chemical unit commonly used to characterize salt concentration in solutions; Ca = calcium, Mg = magnesium, K = potassium, Na = sodium. Electrical conductivity (EC) is in microsiemens/centimeter (µS/cm). SAR = sodium adsorption ratio, % N = nitrogen percent, % C = carbon percent, C:N = carbon:nitrogen ratio. An asterisk (*) denotes a significant change between pre- and post-fire value within that soil horizon ($\alpha<0.05$).

Figure 17. Among the four soil series at RRS is Kovich. This photo was taken in August 2014, just over two years following the Arapaho Fire, and it shows how vegetation in wet meadows responds quickly. See Munn et al., 2018, for a detailed discussion about the soils of RRS. (Photo by L. Munn)

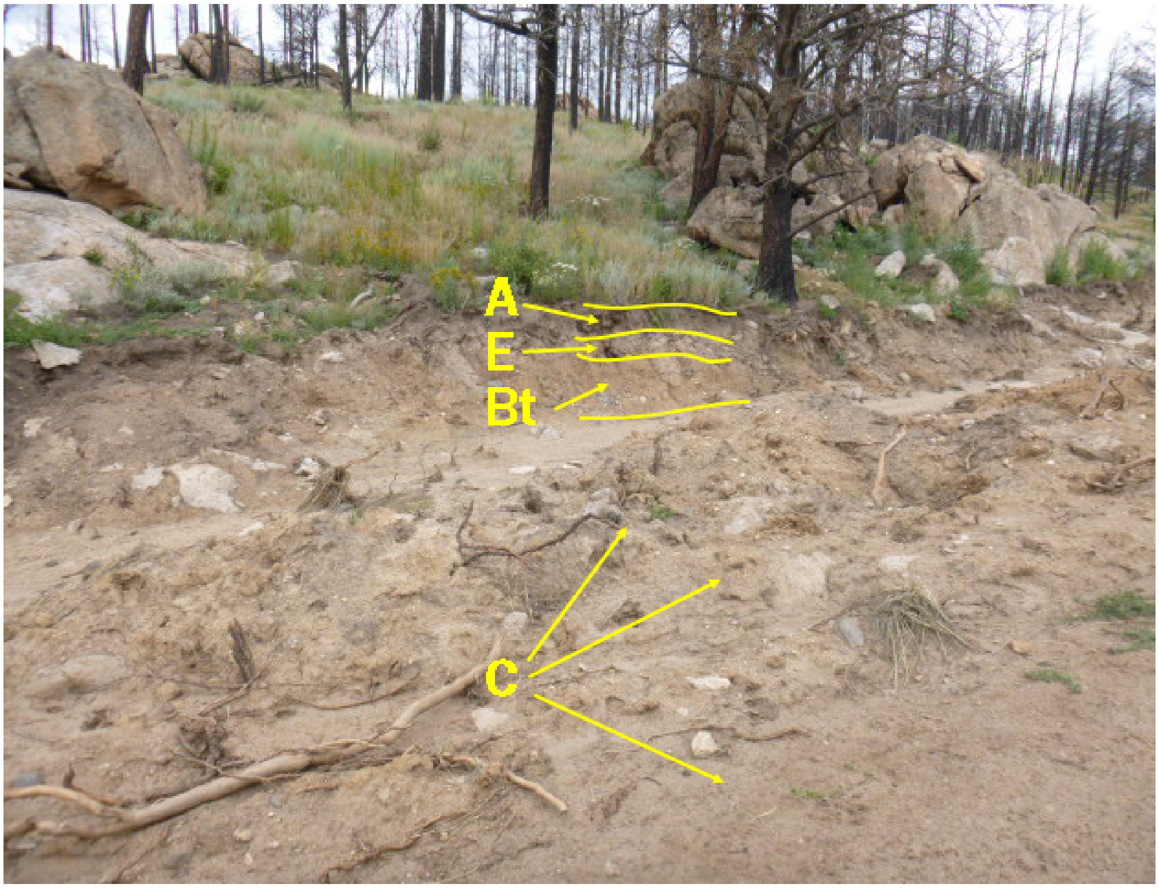

Figure 18. This photo, taken on August 13, 2014, shows the cross-section of a forest soil profile at RRS. The dark layer at the surface is the A horizon, which is the mineral horizon enriched in organic matter. The light-colored layer underneath the A horizon is the E horizon, a layer from which clay has been leached into the subsoil. The reddish-brown under the E horizon is the Bt horizon, a layer of clay accumulation. Underneath the Bt is the unweathered C horizon. The organic litter layer, the O horizon, was consumed by the 2012 Arapaho Fire. Note: If you treated a sample of the A horizon with hydrogen peroxide to dissolve the organic matter, the remaining material would be light-colored, similar to the underlying E horizon. (Photo by L. Munn; graphics overlay by T. Engel)

Figure 19. This photo shows the cross-section of a forest soil profile at RRS, with a vein of granite bedrock (R horizon). The photo was taken on August 13, 2014, just over two years following the Arapaho Fire. (Photo by L. Munn)

Figure 20. This photo (from Williams and Waggener, 2017b) shows a fairly well developed soil profile at RRS. The O horizon is composed of organic debris and partially decomposed organic materials; it extends from the surface to about 4 cm (~1.5 in). The second interval, or A horizon, extends from 4 to 11 cm (~1.5–4.5 in); it contains minerals, but also considerable organic carbon. The third interval (B horizon) is a layer of accumulated clay extending from 11 to 17 cm (~4.5–7 in). From 17 cm (7 in) and deeper (out of the photograph) is the C horizon; here, the parent material is a sandy substrate. (Photo by S. Williams)

Figure 21. University of Wyoming student Michael Curran digs a soil pit in 2011 as part of this and other soil studies at RRS. Fortunately, much data had been collected prior to the 2012 Arapaho Fire, which is allowing researchers to examine how soils change following a high-intensity wildfire. (Photo by S. Williams, from Waggener, 2017)

Figure 22. UW students taking a 2012 forest and range soils course taught by lead author S. Williams examine soil properties at RRS approximately three months after the Arapaho Fire burned through the site. Their examination included soil texture (determined by hand), pH, electrical conductivity, and depth of soil horizons. (Photo by S. Williams)

Gómez-Rey and Gonzalez-Prieto (2013). Their research compared unburned sites to burned soils, and found that N mineralization rates remained significantly higher in burned soils over a 14-day period following fire. This pulse did decrease with time, but remained significant during their study. Soil labile-N, ammonium, and nitrate typically increase in the year following wildfire due to the release of organic-bound N from plant litter, soil organic matter, and biomass (Choromanska and DeLuca, 2001; Certini, 2005; Hart et al., 2005). This increase in mobile N leads to losses from the organic soil horizons due to leaching and runoff. Nitrate (NO_3^-) is especially susceptible to leaching mainly because this anion (a negatively charged ion) is repelled by the normally negatively charged exchange sites on clay particles in the soil. The soil nitrate pulse typically occurs within one year following a burn (Certini, 2005), and NO_3^- concentrations remain high in intensely burned soils for several years as the combined effect of soil heating and a longer term flush of ammonium affect the activity of nitrifiers (Choromanska and DeLuca, 2001). Nitrifying bacteria often very rapidly transform NH_4^+ to NO_3^-. They become very active post-fire not only because of the release of ammonium during the burning process, but also because competition for ammonium by plants is reduced (Neary et al., 1999). Other significant changes in N cycling in the system include vegetation shifts from high-lignin, low-N inputs of ponderosa pine needles and woody biomass, to post-fire herbaceous shrubs, which are relatively much higher in labile N and lower in lignin. Long-term monitoring of the soil inorganic N across these sites will provide further understanding of microbial N cycling across a several year period.

Soil microbial community mortality during fire is caused by both indirect and direct effects of heating (Korb et al., 2004), and as fire intensity escalates, microbial biomass mortality often increases (Dooley and Treseder, 2012). Different fire adaptations in those organisms inhabiting surface soils lead to varying responses to this heating—some groups experience debilitating population losses, while others may actually increase in number. In particular, fungal biomass may be more negatively affected than total microbial biomass or bacterial biomass, and some bacterial groups may actually increase after heating (Bååth et al.,1995; Dooley and Treseder, 2012). Some of the indirect fire effects are through changes in soil biogeochemistry, e.g., increased soil pH after fire can increase the activity of bacteria,

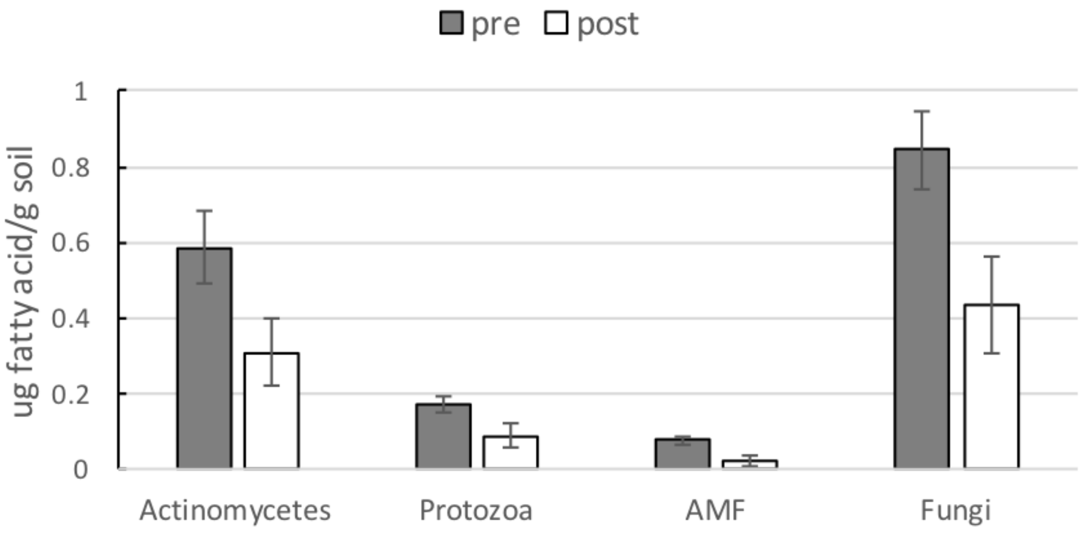

Figure 23. Mean pre- and post-fire phospholipid fatty acid signatures for actinomycetes, protozoa, arbuscular mycorrhizal fungi (AMF), and fungi. The five ponderosa pine sample sites at RRS are included. Error bars represent standard error ($n = 5$). Actinomycetes ($p = 0.037$, $t = -2.32$) and protozoa ($p = 0.006$, $t = -3.25$) were significantly reduced at $\alpha < 0.05$. AMF ($p = 0.094$; $t = -1.81$) and fungi ($p = 0.0937$; $t = -1.81$) showed significant decreases post-fire at an alpha of 0.10. μg = microgram; g = gram. (Figure by Linda van Diepen)

while fungi dominate at a lower pH. Thus, the higher pH post-fire combined with the soil N pulse may increase bacterial abundance, outcompeting fungi for resources (Dooley and Treseder, 2012). This is potentially related to observed long-term fungal community depression following fire (Holden et al., 2013; Kurth et al., 2013).

The results of this study showed no significant difference between pre- and post-fire total abundance of PLFAs. Bacterial PLFA signatures neither increased nor decreased, but a loss was observed in actinomycetes abundance (Fig. 23). The dominant mycorrhizal fungi present in soils under ponderosa pine stands are likely ectomycorrhizal in nature. Since the fire destroyed much of the standing—and ultimately the belowground root biomass—the loss of the fungal PLFAs could partially be due to the severing and subsequent removal of physical connections of these fungi with plant roots. Since the soil samples taken post-fire were collected so quickly after the burn, the measured mortality of these groups may also be due to the direct effects of heating, loss of soil moisture, and other micro-site alterations.

FURTHER STUDIES

After observing marked soil chemical and biotic changes following the Arapaho Fire, we became interested in exploring the subsequent effect these changes might have on the soil microbial communities. One question that arose is: will the depression of fungal and protozoan populations persist over several seasons, or will the conditions such as the flush in soil nutrients stimulate community growth? How might the addition of external soil amendments affect the system? In agricultural soil systems, farmers often apply various fertilizers, microbial inoculum, and organic C substrates to ameliorate the soil microbial and nutritional environment for subsequent planting. We hypothesized that similar environmental enhancements could be achieved using these amendments on fire-disturbed forested systems. The intention of amendment addition in this study was to stimulate and enhance soil microbial activity, particularly that of communities significantly depressed by the Arapaho Fire. The design and outcomes of this study are detailed in RRS Bulletin 8, *Soil amendment addition and microbial community recovery following high-severity fire, Rogers Research Site, north Laramie Mountains, Wyoming* (in production).

ACKNOWLEDGMENTS

We thank the reviewers, Joey Knelman, Ph.D., Institute of Arctic and Alpine Research, whose specialties include microbial ecology, soil microbiology, and biogeochemistry; and Stephanie Winters, M.S. student in soil science, University of Wyoming Department of Ecosystem Science and Management. Appreciation is extended to Kelli Belden, research associate and director (now retired) of the former UW Soil Testing Laboratory for analyzing soil cations, and to Caley Gasch, Leann Naughton, and Rachana Giri Paudel for their help in sample analysis. Assisting with various field operations were Christine Sednek, Dave Rider, Michael Curran, and Jesse Hahm. David Legg, statistician in the UW Department of Ecosystem Science and Management, helped with statistical design, while Brian Mealor, associate professor in the UW Department of Plant Sciences and director of the Sheridan Research and Extension (R&E) Center, helped to lay out the study conceptually. Stan Bellgard, a plant pathologist from Landcare Inc., New Zealand, helped with soil sampling in 2012. Mick Mickelson, who lives near RRS, has proved to be the finest of neighbors in times of need at this remote site.

Much gratitude is extended to UW Extension's Office of Communications and Technology for a variety of assistance. Graphic designer Tanya Engel has spent many hours on each and every bulletin, helping in a variety of ways, including bulletin layout and design, and figure and table development. Ann Tanaka, website designer/developer, has overseen the posting of each bulletin on the SAREC website at http://bit.ly/RogersResearchSite. Steve Miller, senior editor in the office, and Chavawn Kelley, writer/editor, have worked with us on news release distribution.

Josh Decker, manager of UW Real Estate Operations, and his staff have provided valuable assistance throughout work on the RRS bulletin series. The former Upper Midwest Aerospace Consortium furnished the high spatial resolution AEROCam photographs. These images were taken as part of a vegetation mapping project through the WyomingView program headed by the Wyoming Geographic Information Science Center on the UW campus. Helping to fund this project were the Wyoming Agricultural Experiment Station (WAES), the U.S. Geological Survey, and AmericaView Inc. The aerial image of RRS and surrounding lands is from the National Agriculture Imagery Program (NAIP). Leslie Waggener has provided support and guidance throughout development of the entire RRS bulletin series.

We offer a 'click of the shutter' to those who took photos appearing in the bulletin: in addition to co-authors Larry Munn and Steve Williams, they include Colleen Hogan, a friend of Colonel William C. Rogers; Mollie Herget, who conducted research at RRS while a graduate student at UW; Josh McGee, incident commander of the Arapaho Fire; Michael Curran, UW graduate student who helped with soil sampling and many other tasks associated with this project and other studies at RRS; UW student Elizabeth Traver; Jim Freeburn, former SAREC director who is now the regional training coordinator for Western Sustainable Agriculture Research and Education; and Dorothy Tuthill, associate director of the UW Biodiversity Institute and Berry Biodiversity Conservation Center on the UW campus.

We extend much appreciation to Bret Hess, WAES director and interim dean in the UW College of Agriculture and Natural Resources, and John Tanaka, SAREC director and WAES associate director, for providing the necessary resources to bring this and other RRS research projects (and subsequent

bulletins) to fruition. During this study, Frank Galey, former dean of the UW College of Agriculture and Natural Resources, provided incentive and support to develop RRS into a site for extension, research, and teaching. Funding for this research came from WAES, the College of Agriculture and Natural Resources, and the UW Department of Civil and Architectural Engineering.

Finally, we owe a great deal of gratitude to Colonel William C. Rogers for donating his land in the Laramie Mountains to the University of Wyoming for research, extension, teaching, and other activities. For it was his gift that is allowing students, faculty, staff, and others to expand their knowledge, and may this knowledge help to improve the forestry, wildlife, and other natural resources at the Rogers Research Site, Laramie Mountains, and beyond for generations to come.

A variety of forbs and grasses were well established at RRS by August 2014, just over two years following the high-intensity Arapaho Fire, but noxious weeds also became more prevalent, including Canada thistle (*Cirsium arvense*), the plants on the right side that have purplish tops. On the left side is a wild turkey (*Meleagris gallopavo*), which is among the many resident wildlife species that occupy RRS and surrounding lands in the north Laramie Mountains. (Photo by L. Munn)

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APPENDIX A. RAW RRS PRE- AND POST-FIRE SOILS DATA.

Site	Horizon	pre-post	NO_3 N(mg/kg)	NH_4^+N(mg/kg)	pH	EC	Ca (meq/L)	Mg(meq/L)	K(meq/L)	Na(meq/L)	SAR	PO_4^{3-}P(mg/kg)	Wt% N	Wt% C	C/N ratio
1	A	pre	5.19	8.89	5.82	0.19	0.56	0.26	0.08	0.95	1.47	13	0.33	4.5	13.8
1	B	pre	6.66	13.94	5.9	0.27	0.71	0.26	0.32	1.04	1.5	12	0.04	0.4	10.7
1	B	pre	3.59	5.38	6.28	0.14	0.29	0.24	0.15	0.59	1.14	11	0.11	0.9	8.0
2	A	pre	4.74	17.16	6.84	0.14	0.9	0.43	0.29	0.89	1.09	50	0.39	6.2	15.9
2	A	pre	7.81	5.08	6.21	0.15	0.45	0.47	0.33	0.85	1.25	24	0.16	1.5	9.7
2	B	pre	4.84	12.19	5.87	0.17	0.5	0.15	0.18	0.76	1.32	20	0.13	1.1	8.3
2	B	pre	8.54	6.93	6.49	0.12	0.44	0.36	0.21	0.53	0.85	17	0.05	0.6	12.3
3	A	pre	1.12	1.93	6.62	0.19	0.63	0.23	0.29	0.74	1.12	34	0.07	1.5	20.3
4	A	pre	5.90	2.99	6.67	0.33	2.08	0.62	0.28	0.82	0.71	23	0.08	1.9	22.8
5	A	pre	6.03	8.78	5.71	0.2	1.14	0.37	0.33	0.28	0.33	46	0.22	4.0	18.4
5	B	pre	4.21	3.65	5.79	0.39	2.53	0.85	0.37	0.79	0.61	36	0.08	1.6	21.3
6	A	pre	5.72	6.28	5.94	0.28	1.87	0.54	0.24	0.89	0.81	11	0.11	2.0	18.4
6	A	pre	3.00	3.79	6.18	0.59	4.15	1.42	0.48	0.55	0.33	21	0.25	3.9	15.8
7	A	pre	1.32	5.56	5.42	0.47	3.21	1.29	0.4	0.93	0.62	25	0.29	5.8	19.8
7	B	pre	3.77	4.30	5.68	0.19	0.71	0.3	0.22	0.95	1.34	13	0.05	0.5	11.2
8	A	pre	39.99	6.97	5.14	0.19	0.83	0.45	0.34	0.6	0.75	56	0.23	3.9	17.1
8	A	pre	15.63	5.36	5.97	0.11	0.37	0.14	0.06	0.59	1.17	37	0.10	2.0	19.6
8	B	pre	20.97	5.33	5.48	0.12	0.49	0.18	0.04	0.8	1.38	23	0.04	0.5	13.2
1	A	post	7.17	37.65	7.54	1.1	9.25	3.52	1.32	0.65	0.26	184	0.85	12.6	14.8
1	B	post	3.01	2.46	5.96	0.48	1.89	0.73	0.23	0.80	0.70	27.8	0.45	6.1	13.6
2	A	post	10.24	24.07	7.53	1.19	15.76	7.78	2.43	0.32	0.09	228	0.93	16.3	17.6
2	A	post	10.38	7.08	5.97	0.31	1.51	0.64	0.31	0.45	0.43	37.2	0.43	6.1	14.3
2	B	post	4.18	7.23	5.8	0.26	1.36	0.50	0.25	0.48	0.50	26.6	0.19	2.0	10.8
3	A	post	16.83	3.05	5.85	0.19	1.45	0.48	0.18	0.39	0.40	24.3	0.07	1.6	22.3
4	A	post	19.27	6.64	5.98	0.2	1.40	0.43	0.18	0.16	0.16	17.8	0.19	3.0	16.0
4	A	post	21.92	16.75	7.98	3.11	23.41	13.14	1.81	0.47	0.11	171	0.35	3.2	9.0
4	B	post	4.27	5.19	5.66	0.2	1.12	0.49	0.11	0.25	0.28	16.9	0.04	0.7	16.7
5	A	post	16.04	21.69	7.31	1.52	15.01	6.27	1.33	0.33	0.10	121	0.51	6.5	12.7
5	A	post	3.93	7.25	6.09	0.38	3.28	0.96	0.29	0.16	0.11	27.1	0.05	0.9	16.5
6	A	post	9.84	24.84	6.97	1.81	15.02	4.51	1.28	0.31	0.10	74	0.34	4.4	12.7
6	A	post	13.57	12.64	6.03	0.6	4.10	1.22	0.51	0.23	0.14	39.1	0.18	2.4	13.1
7	A	post	18.97	16.93	6.68	0.56	6.22	2.43	0.71	0.47	0.23	50.9	0.37	7.5	20.1
7	B	post	5.86	5.33	6.67	0.26	1.35	0.52	0.19	0.49	0.51	17.9	0.05	0.5	11.1
8	A	post	187.39	21.52	5.29	0.44	1.51	0.64	0.47	0.15	0.15	105	0.28	4.5	15.9
8	B	post	37.05	5.23	5.54	0.131	1.87	0.45	0.18	0.39	0.37	38.6	0.06	0.8	14.0

Site Descriptions

- 1 = riparian area
- 2 = aspen grove
- 3 = dense ponderosa pine
- 4 = rocky outcrop (this site included a small—but dominant—presence of ponderosa pine)
- 5 = open ponderosa pine
- 6 = open ponderosa pine
- 7 = aspen grove
- 8 = dense ponderosa pine.

Horizon Details

- A = A horizon, which extends from about 4 to 11 cm (~1.5–4.5 in). The A horizon contains minerals, but also considerable organic carbon. This horizon is directly beneath the surface soil, called the O horizon, which is composed of organic debris.
- B = B horizon, which is the third interval in the soil profile. This horizon is a layer of accumulated clay extending from about 11 to 17 cm (~4.5–7 in).

Abbreviations

- pre = soil samples collected prior to the Arapaho Fire, which burned across RRS lands July 2–3, 2012
- post = soil samples collected following the fire
- NO_3^-N = nitrate nitrogen
- NH_4^+N = ammonium nitrogen
- pH = potential hydrogen
- EC = electrical conductivity
- Ca = calcium
- Mg = magnesium
- K = potassium
- Na = sodium
- SAR = sodium adsorption ratio
- PO_4^{3-}-P = phosphate phosphorus
- Wt% N = nitrogen content
- Wt% C = carbon content
- C/N ratio = carbon/nitrogen ratio
- mg/kg = milligram/kilogram dry soil
- meq/L = milliequivalents per liter, a chemical unit commonly used to characterize salt concentration in solutions.

The moderate- to high-intensity Arapaho Fire, which burned across the Rogers Research Site on July 2–3, 2012, reached temperatures of nearly 900°F (500°C) in some places. Fortuitously, a University of Wyoming research team composed of students and faculty members had collected soil samples from several pre-determined plots prior to the lightning-caused fire, which allowed them to compare soils pre- and post-fire. That research is detailed in this bulletin, while a subsequent project examining soil amendment additions and microbial community recovery following the fire will be detailed in RRS Bulletin 8. (Photo by Steve Williams)