QUANTIFYING PHYSICAL CHANGES IN

NEAR-SURFACE SOIL DURING PRESCRIBED FIRE

by

ERIK R. ANDERSON

Bachelor of Arts, 2014
University of San Diego
San Diego, California

Submitted to the Graduate Faculty of the
College of Science and Engineering
Texas Christian University
in partial fulfillment of the requirements
for the degree of

Master of Science

May 2016

QUANTIFYING PHYSICAL CHANGES IN
NEAR-SURFACE SOIL DURING PRESCRIBED FIRE

by

Erik Anderson

Thesis approved:

Major Professor

For The College of Science and Engineering

ACKNOWLEDGEMENTS

I would like to thank Dr. Mike Slattery for his continuous guidance and support during the planning and execution of my thesis research. I feel blessed and lucky to have had the opportunity to research with someone who values the process of discovery and believed in me every step of the way. Thank you Rob Denkhaus for not only helping me with field work at the Fort Worth Nature Center and Refuge, but also introducing me to various methods and including me in the nature center family. And thank you Tamie Morgan for your assistance with GIS and GPS methods during my research, and for your consistent input to develop my project and presentations.

This project was only possible because of the work by Eddy Wood, the Azle Fire Department, and the Briar Volunteer Fire Department during the prescribed burn in Azle, Texas. Eddy, thank you so much for your generous hospitality.

Thank you Dr. Omar Harvey for your advice in designing my experimental approach and interpretation of the data. Also, thanks to Michelle Villafranca, Nic Martinez, Nick Griffin, Sharra Blair-Kucera, Shawn Kucera, Daniel Shelley, Esther Chitsinde, Jon Scott, and Katie Smith for your assistance in the field. This project would not have been completed without your help.

Finally, I would like to thank my family and friends who offered much needed moral support on many occasions. This research is for the people that got me interested in our natural world from a young age. Without you I would have never been inspired to explore.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Introduction

Beginning in the early twentieth century, programs to suppress and prevent wildland fires have altered natural fire regimes. These actions can cause a significant buildup of fuels, potentially setting the stage for catastrophic fires (Boerner et al. 2008). In order to reduce fuel loads and limit potential fire danger, prescribed fires are conducted to remove accumulated vegetation (Fernandes and Botelho 2003). Prescribed fires are also used to mimic naturally occurring fires to maintain vegetative species and wildlife habitats in fire-dependent ecosystems (Stephens and Fry 2005). Prescribed fires are becoming more common among land managers to control invasive vegetative species and maintain prairie ecosystems (Grace et al. 2005; Knapp, Estes, and Skinner 2009; Teague et al. 2008).

Although personnel pay careful attention to potential adverse effects when planning and conducting prescribed fires, unanticipated negative outcomes remain possible. For example, while management may use prescribed fires to increase biodiversity and stimulate growth of native vegetation, these results are not always achieved as well as anticipated (Hutchinson et al. 2005). Because exotic species such as *Bromus tectorum* and *Tamarix* are able to thrive following fire, prescribed fires conducted in areas where these species are abundant may increase their dominance over native vegetation (Melgoza, Nowak, and Tausch 1990; Smith et al. 2009). Also, while native to the United States, smooth sumac (*Rhus glabra* L.) recovers quickly after fire, potentially increasing its abundance in post-fire vegetative communities; thus, prescribed fire should not be used to control this species (Ortmann et al. 1997).

Removal of vegetation by fire may lead to increased soil erosion and sediment transport, potentially causing adverse effects on water quality (Vega, Fernandez, and

Fonturbel 2005). Many prescribed burns are conducted to remove the duff layer and allow native species to germinate in the blackened soil. However, removing the duff layer can limit the water holding capacity of surface soil and may increase the risk of soil erosion, especially following severe fires (Hille and Stephens 2005; Robichaud 2000). In addition, high levels of particulate matter, carbon monoxide, volatile organic compounds, and other air pollutants emitted during prescribed fires can pose threats to local communities (Lee et al. 2005). If prescribed fires do not achieve desired outcomes or negatively impact the landscape, burns may have unwanted effects on the environment while posing unnecessary threats to personnel (Bradstock and Auld 1995; Penman and Towerton 2008).

Monitoring changes in soil characteristics during prescribed fires is important because changes in soil nutrients, temperature, and moisture content control post-fire vegetative response, in turn affecting species that depend on post-fire vegetative growth for food and habitat (Certini 2005; Huang and Boerner 2008; Massman, Frank, and Mooney 2010; Savage and Vermeulen 1983; Thomas et al. 2010). Temperatures reached in soil during fires are influenced by fire duration (based on weather patterns, fuel characteristics, and firing techniques), soil depth, and soil moisture content. The greatest temperature changes are typically achieved at shallow depths (< 5 cm) and low soil moisture content (< 20%) (Busse et al. 2005). Peak temperatures reached at the soil surface tend to range from 200 - 700°C, with higher temperatures recorded during burns at higher fuel loads with low soil moisture content (Preisler, Haase, and Sackett 2000; Ryan and Noste 1985; Stoof et al. 2011a). Soil temperatures are likely to be greatest during summer burns due to the lack of soil moisture, causing greater damage to vegetation than burns conducted during winter or early spring (Britton, Clark, and Sneva 1983; Vermeire et al. 2005). Summer fires are typically used to remove invasive vegetation because the temperatures achieved in surface soil are able to exceed the 60°C threshold for root mortality (Busse et al. 2010; Vermeire, Crowder, and Wester 2011). Volumetric soil moisture content greater than 20% can restrict the increase in soil temperature below the lethal threshold for vegetative root structures (Busse et al. 2010; Frandsen and Ryan 1986).

Techniques used to conduct prescribed fires are likely to cause different increases in soil temperature in certain locations within the burned area. Head fires (fires traveling in the same direction as the wind) may pass over the surface with high intensity, having limited time to heat the soil. However, back fires (fires traveling against the wind) may creep slowly over the surface, enabling them to cause increased temperatures at greater depths in the soil profile (Raison 1979). Further, this difference in rate of spread can cause temperature increases in near-surface soil during back fires to last longer than changes in soil temperature achieved during head fires. Soil temperatures were found to exceed 60ºC at depths up to 3 cm during slow moving fires (Bradstock and Auld 1995), indicating that back fires may allow temperature increases to persist for longer periods of time.

Following fire, soil moisture content may increase due to the lack of vegetation; limited vegetative cover can, in turn, increase the amount of precipitation that reaches the soil surface and decrease plant uptake, allowing more water to remain in the soil (Cardenas and Kanarek 2014; Romo et al. 1993). Frequent burns (5-year interval) and fires conducted during early spring have been shown to preserve soil moisture content by restricting transpiration (Hatten et al. 2012), potentially providing adequate water resources for willow (*Salix bebbiana*) and other vegetative species that depend on high soil moisture content (Mullen, Springer, and Kolb 2006).

On the other hand, fires can darken the soil surface, thereby increasing heat absorption and evaporation and decreasing soil moisture content (Iverson and Hutchinson 2002; Redmann et al. 1993). While darkening the soil surface can increase soil temperatures and thereby extend the duration of the growing season, fires may have detrimental effects on vegetation during dry periods by further restricting soil moisture content (Redmann 1978). Low soil moisture content following burns may allow vegetative species that perform well during low water availability to outcompete other species (Pelaez et al. 2001).

Soil water repellency can greatly limit the amount of water capable of penetrating the soil surface. This phenomenon occurs when heated organic matter surrounds soil particles and is typically most pronounced in coarse-grained soils heated to 175 - 200°C (Doerr, Shakesby, and Walsh 2000; Doerr et al. 2006). By restricting infiltration, soil water repellency can lead to increased runoff, soil erosion, and sediment transport (Stoof et al. 2011b). While temperatures greater than 200°C can destroy water repellent soil layers, the low fire intensities achieved during prescribed fires may facilitate the formation of water repellent layers and restrict infiltration capacity following burns (DeBano and Krammes 1966).

Although previous research has examined fire-induced changes in soil temperature and moisture content, there are several gaps in the current understanding of how soils respond to prescribed fires. Most studies conducted during prescribed fires only examine soil temperature fluctuations and many have concentrated on Mediterranean ecosystems (e.g., Rubio, Úbeda, and Ferrer 2012; Uribe et al. 2013). In addition, models constructed to predict changes in soil temperature and moisture content are often based on laboratory experiments (Aston and Gill 1976; Ebel 2013; Massman 2012, 2015; Preisler, Haase, and Sackett 2000);

these models lack sufficient comparisons to field measurements of soil moisture content and water potential during prescribed fires. Moreover, studies that examined changes in soil moisture content due to prescribed fires present varying results; for example, plant-water interactions have been shown to both improve and worsen with varying fire severity and frequency (Neary et al. 1999). In addition, many studies do not include data to characterize pre-fire soil conditions or monitor changes in water potential during prescribed fires (Doerr, Shakesby, and Walsh 2000). Because the environmental impacts prescribed fires have on near-surface soil are site specific, it is important to study the effects of this land management practice in diverse areas where it is frequently used (Robichaud 2000; Shakesby et al. 2003).

In order to address these gaps in the current understanding of how prescribed fires impact soil properties, the objectives of this study were to (1) quantify how soil physical properties – namely, near-surface soil temperature (°C), soil moisture content (%), water potential (kPa), infiltration capacity (mm hr^{-1}), and aggregate stability (%) – respond during and immediately following prescribed fires, (2) offer a comparison between results from experimental fires and results obtained during a prescribed burn conducted in the field, and (3) provide a proof-of-concept for methods that can be used to efficiently conduct longer-term studies examining fire-induced changes in near-surface soil moisture content, water potential, and infiltration capacity. The results from this study were also compared to models that predict changes in soil moisture content during soil heating to test the validity of existing models against field conditions.

Methods

Experimental design

Field data was collected during a prescribed burn near Azle, Texas (32°55'12" N, 97°32'51" W), conducted on September 12, 2015 (hereafter referred to as the Azle Prairie Fire) (Figure 1). Subsequently, experimental burns (hereafter referred to as the Box Fire) were conducted in four wooden 1.2 x 1.2 x 0.12 m boxes on December 16, 2015 (Table 1). Soil transported from the site of the Azle Prairie Fire (Table 2) was sieved using a 2.46 mm stainless steel wire mesh (Figure 2) (McNichols Co., Tampa, FL) and packed into the boxes (bulk density: 1.23 ± 0.04 g cm^{-3}; all measurements are given with the corresponding standard error of the mean). After packing soil into the boxes, the soil was wetted prior to burning to raise the soil moisture content to approximately 15%; this allowed for the observation of changes in soil moisture while not exceeding 20% soil moisture content, which may reduce the peak temperatures achieved during fire (Busse et al. 2010).

Figure 1. The Azle Prairie Fire was conducted near the eastern border of Parker County, Texas. Soil from this site was used for all prescribed fires conducted in this study.

Parameter	Azle Prairie Fire	Box Fire
Date	9/12/2015	12/16/2015
Time of day	12:05 – 2:00 PM	12:54 – 1:10 PM
Fuel moisture	36.8 ± 2.4%	8.2%
Fuel load	1.7 T $acre^{-1}$	0, 0.5, 2, and 5 T $acre^{-1}$
Fire type	Head fire	Head fire
Rate of fire spread	0.5 m s^{-1}	102, 164, 243 s
Maximum flame height	1.3 m	0.3, 0.8, 1.2 m
Air temperature	28.6 ± 0.4°C	14.9°C
Relative humidity	43.3 ± 2.2%	45.9%
Average wind speed	0.8 ± 0.2 m s^{-1}	0.7 m s^{-1}
Maximum wind speed	2.1 ± 0.3 m s^{-1}	2.5 m s^{-1}

Table 1. Weather and fuel conditions during fires. Data for the Azle Prairie Fire are average values (n = 4). Rate of spread during the Box Fire was measured by timing the flame duration while burning each box. Fuel load at the Azle Prairie Fire was estimated using the Country Fire Authority Grassland Curing Field Card (2014).

Soil type	Taxonomic class name	Order	Suborder
Duffau and Weatherford	Fine-loamy, siliceous, thermic Udic Paleustalfs	Alfisols	Ustalfs
Geomorphic description	**Slopes**	**Albedo value**	**Hydrologic group**
Ridges on hills	2 - 8%	0.185	B

Table 2. Soil type at the site of the Azle Prairie Fire (used for all burns).

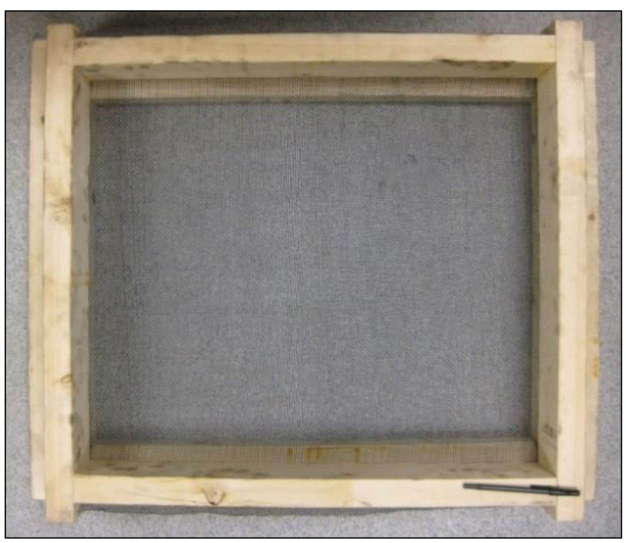

Figure 2. 60 x 75 cm stainless steel wire mesh (2.46 mm opening) used to sieve soil for the Box Fire. The wire mesh was stapled between two wooden frames built from 5 x 10 x 65 cm lumber, and 7.6 cm long screws were used to secure the frames together.

One box was left unburned and clipped vegetation was used to prepare the following three fuel loads in the remaining boxes: 0.5 T $acre^{-1}$ (163.8 ± 0.2 g), 2 T $acre^{-1}$ (648.0 ± 0.3 g), and 5 T $acre^{-1}$ (1616.5 ± 0.6 g). The clipped vegetation used in the Box Fire consisted of native grass species, including Indiangrass (*Sorghastrum nutans*), switchgrass (*Panicum virgatum*), and little bluestem (*Schizachyrium scoparium*), which was comparable to the fuel burned during the Azle Prairie Fire (Figure 3). To mimic prairie vegetation, larger pieces of hay were planted several centimeters into the soil and smaller pieces of hay were placed on top of the soil surface (Figure 4). All burns during the Box Fire were ignited using a propane torch. Unburned vegetation was only reignited during the 0.5 T $acre^{-1}$ burn because there was not sufficient fuel load to carry the fire (Figure 5).

Figure 3. Beginning of head fire during the Azle Prairie Fire.

Figure 4. Adding vegetation to prepare 0.5, 2, and 5 T acre^{-1} fuel loads prior to the Box Fire.

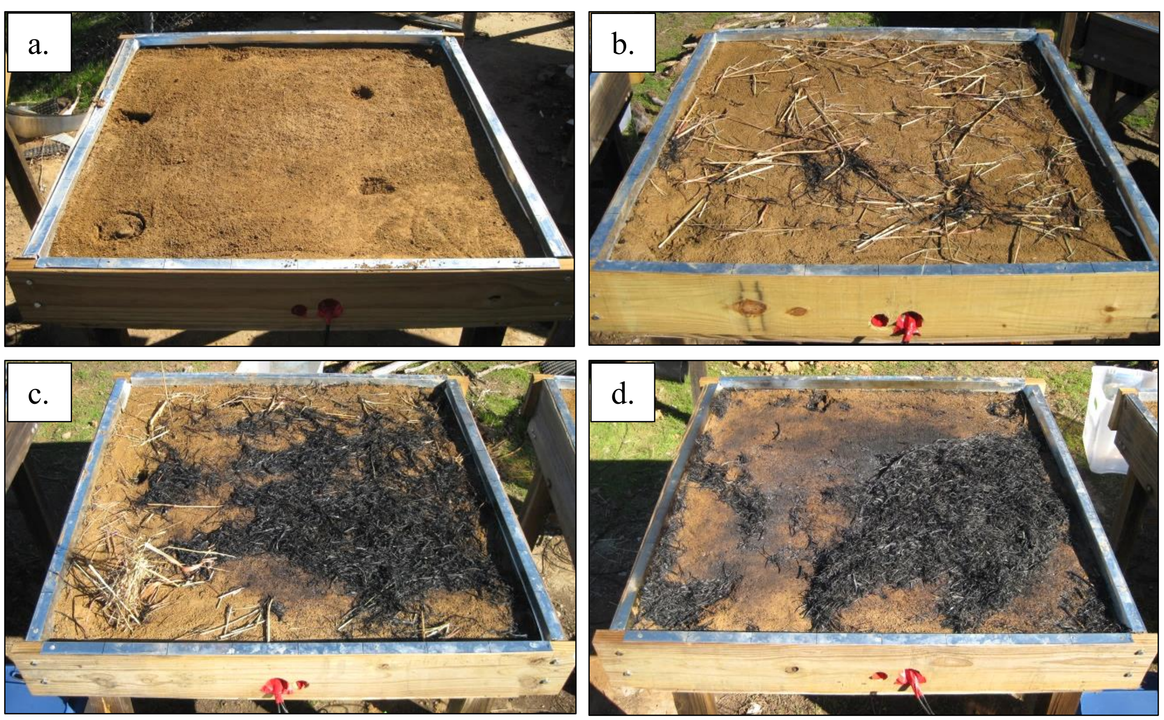

Figure 5. Post-burn images from the (a) unburned box, (b) 0.5 T acre^{-1} box, (c) 2 T acre^{-1} box, and (d) 5 T acre^{-1} box.

Rainfall was negligible during the first week following the Azle Prairie Fire. To block precipitation from entering the boxes after the Box Fire, covers were constructed from plywood and plastic sheets (Figure 6). These covers were only used during the fourth day following the Box Fire.

Figure 6. Plywood covers (1.5 m^2) were used to prevent precipitation from entering the boxes during the fourth day following the Box Fire. Covers were lined with plastic sheets and were nailed to 10 cm tall boards on the corners of all boxes.

Data collection: Soils

SM200 soil moisture sensors (accuracy: ± 3%), SM300 soil moisture and temperature sensors (accuracy: ± 2.5%; 0.5°C), ST1 soil temperature sensors (accuracy: ± 0.2°C), and EQ2 equitensiometers (accuracy: ± 10 kPa) (Dynamax Inc., Houston, TX) were deployed several hours prior to the Azle Prairie Fire and several days prior to the Box Fire. Sensors were buried along a transect during each fire to cover the greatest area (Figures 7 and 8). Because temperature fluctuations during fire have been shown to be of lower magnitude at greater depths (Choczynska and Johnson 2009; Valette et al. 1994), ST1 soil temperature sensors (maximum temperature: 150°C) were buried at a depth of 3 cm in the field and 2 cm in the boxes, and all other sensors (maximum temperature: 60°C) were buried at a depth of 5 cm in the field and 4 cm in the boxes.

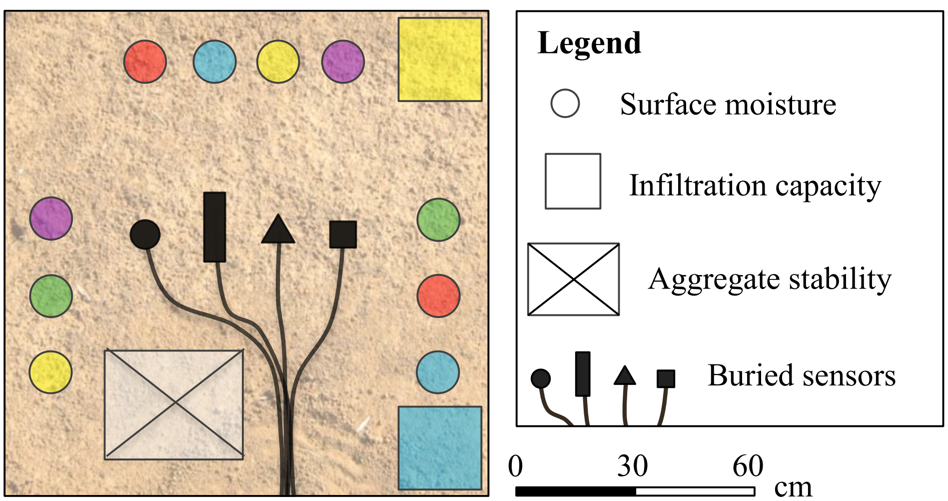

Figure 7. Sensor location map for the Box Fire. Samples of similar color were taken at the same time interval.

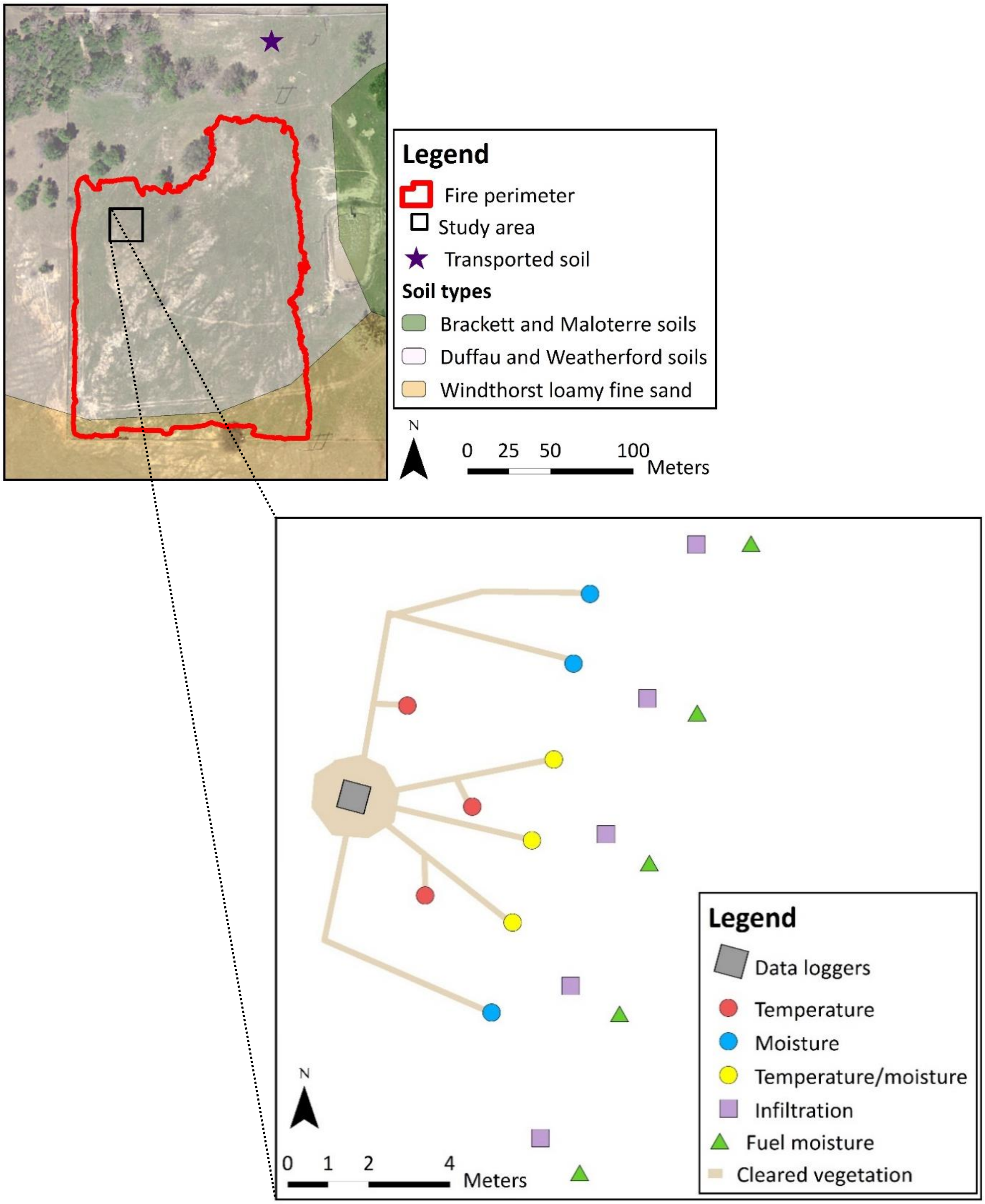

Figure 8. Fire perimeter and sensor location map for the Azle Prairie Fire. Red sensors (ST1 soil temperature sensors) were buried at 3 cm depth, and yellow sensors (SM 300 soil temperature and moisture sensors) were buried at 5 cm depth.

Data was collected from all buried sensors at 2-second intervals during fires and 30-minute intervals following fires, and data was stored on GP1 and GP2 data loggers (Dynamax Inc., Houston, TX). During fires, data loggers were placed in reflective boxes (constructed of punched angle beams and reflective insulation) to protect the instruments from radiant heat (Figure 9). To further protect the equipment during the Azle Prairie Fire, data loggers and their protective boxes were buried in the center of an area cleared to mineral soil with radius equal to the height of the surrounding vegetation. Mattocks, pruning saws, and hand weeders were used to dig narrow trenches (≤ 10 cm wide) to bury wires for all sensors. Sensors were placed at the end of these trenches to keep the sensors as close as possible to vegetation within the burned area.

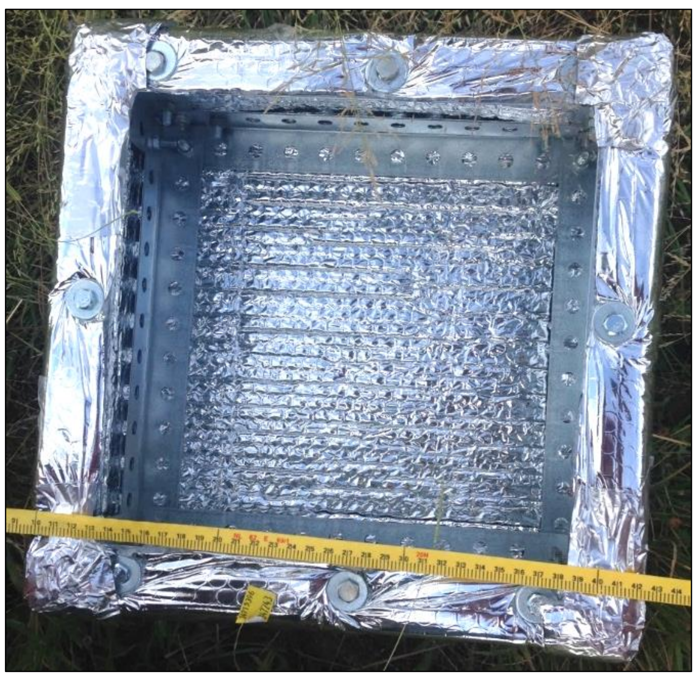

Figure 9. Box constructed of punched angle beams and reflective insulation (32 x 32 x 16 cm) to protect data loggers from radiant heat during fires.

Surface soil moisture content was measured every two days following the Box Fire via grab samples (91.54 ± 1.27 g) at the following depths: 0 - 0.5, 0.5 - 1, and 1 - 2 cm. Soil was taken from two locations within each box and combined into a representative sample from each depth (see Figure 7). Samples were transported to the lab in 100 ml beakers wrapped in foil and oven dried for 24 hours at 105°C. Surface soil moisture content at each time interval was calculated by averaging samples taken from each box.

Infiltration capacity was measured immediately pre- and post-fire at all burns using Turf-Tec Infiltrometers. In order to keep water from reaching the buried sensors, infiltration was measured 2 m away from the senor transect at the Azle Prairie Fire (see Figure 8) and in the corners of each box at the Box Fire (see Figure 7).

Aggregate stability was also measured following the Box Fire using methods adapted from those developed by Le Bissonnais (1996). Samples (21.7 ± 1.8 g) collected from the soil surface before and after each burn were gently sieved to obtain aggregates between 1 - 2 mm, air dried for 12 hours, and weighed prior to analysis. Samples on 1 mm sieves were fully submerged in water for 5 minutes, moving 10 cm vertically through the water column at 10-second intervals. Wet samples were then oven dried for 3 hours at 105°C and reweighed.

Data collection: Fires

Fuel moisture was calculated by collecting five representative samples prior to the Azle Prairie Fire (35.4 ± 1.7 g) and one representative sample of clipped hay used for the Box Fire (31.9 g). Samples were weighed in the field and subsequent weights were recorded in the lab after repeated drying at 10 - 20 second intervals using a microwave oven. Samples were dried and reweighed until three consecutive measurements were within 0.5 g. The average fuel load was determined for the Azle Prairie Fire (approximately 1.7 T $acre^{-1}$) by visually estimating the amount of fuel in 1 m^2 plots over each buried sensor using the Country Fire Authority Grassland Curing Field Card (2014).

Two 1.5 m tall metal posts placed 25 m apart and approximately 10 m from the buried sensors were used to estimate flame height and rate of spread during the Azle Prairie Fire. The fire type (back fire, flank fire, or head fire) was recorded as the fire progressed over the buried sensors. Air temperature, relative humidity, and wind speed were recorded at 30-minute intervals during the Azle Prairie Fire and at the start of the Box Fire using a Kestrel 3000 Pocket Weather Meter.

Data analysis

DeltaLINK 3.1.1 software (Dynamax Inc., Houston, TX) was used to program and download data from the data loggers. Stored data and field measurements of surface soil moisture content were used to create time series to illustrate how volumetric soil moisture content (%), water potential (kPa), and near-surface soil temperature (°C) responded to each burn. Standard curves were created using results from the Box Fire to predict changes in near-surface soil during fires at similar fuel loads. A scatter plot and bar graph were created to demonstrate fire-induced changes in infiltration capacity (mm hr^{-1}) and aggregate stability (%), respectively.

Maps

Maps were created for the Azle Prairie Fire using ArcMap 10.1 (see Figure 8) (ESRI, Redlands, CA). A Trimble GPS unit was used to collect soil sensor locations, fuel moisture and infiltration capacity sampling locations, and the fire perimeter (averaging 50 points for each location). Soils data was downloaded from the Soil Survey Geographic Database Data Downloader (SSURGO 2014), and air photos were downloaded from the Texas Natural Resources Information System (2015). All maps are projected in NAD 1983 State Plane Texas N Central FIPS 4202 (Meters).

Results

Temperature

The increase in soil temperature during all burns was greatest in sensors buried at shallow depths (2 and 3 cm) (Figure 10). During the Box Fire, the maximum soil temperatures achieved at 2 cm depth were 15.9, 26.9, and 73.2ºC at fuel loads of 0.5, 2, and 5 T $acre^{-1}$, respectively. The peak soil temperature during the Azle Prairie Fire at 3 cm depth was 32.3ºC. The 5 T $acre^{-1}$ fire was the only burn to achieve soil temperatures greater than 60ºC; soil temperature at 2 cm depth remained above 60ºC for 7.2 minutes during this fire.

Increases in soil temperatures at greater depths (i.e., 4 and 5 cm) were significantly restricted compared to shallower depths. During the Box Fire, the maximum soil temperatures achieved at 4 cm depth were 15.6, 19.6, and 28.4ºC at fuel loads of 0.5, 2, and 5 T $acre^{-1}$, respectively. The peak soil temperature during the Azle Prairie Fire at 5 cm depth was 28.2ºC. While soil temperatures at 4 and 5 cm depths did not reach temperatures recorded at shallower depths, temperature increases at greater depths were maintained for a much longer time, especially in the 2 and 5 T $acre^{-1}$ boxes.

The increase in soil temperature at the 4 and 5 cm depths was achieved after the increase in soil temperature at the 2 and 3 cm depths during each burn. During the 0.5 T $acre^{-1}$

fire, the peak soil temperature at 4 cm depth was achieved 6.9 minutes after the peak soil temperature at 2 cm depth. This lag time was greater during the 2 T acre^{-1}, 5 T acre^{-1}, and Azle Prairie Fire, as the peak soil temperatures at 4 and 5 cm depths were achieved 14.4, 14.0, and 14.5 minutes, respectively, after the peak soil temperatures at 2 and 3 cm depths.

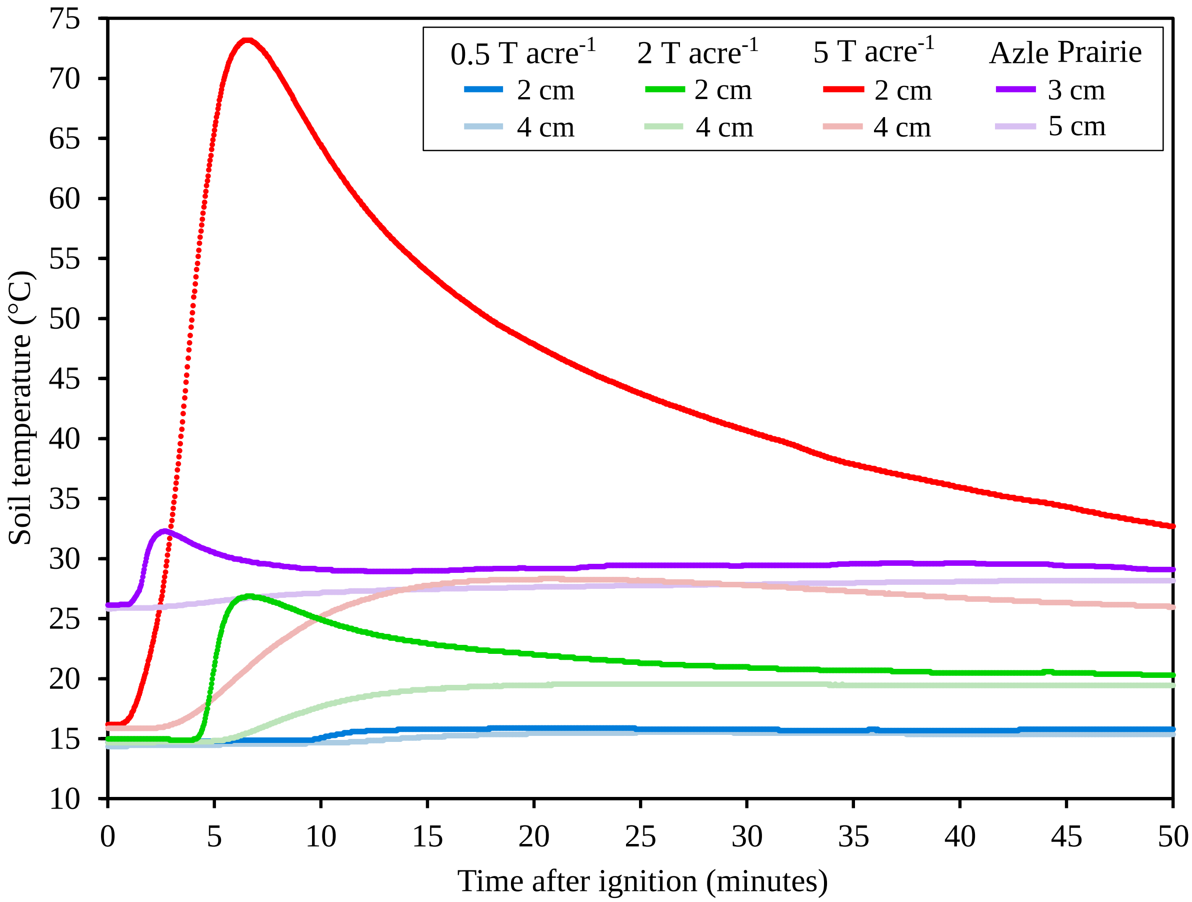

Figure 10. Soil temperature during fires. Measurements taken from ST1 sensors (2 and 3 cm depths) and SM300 sensors (4 and 5 cm depths) at 2-second intervals.

Standard curves constructed from soil temperature data suggest that the change in soil temperature during fire is related to the fuel load burned and depth beneath the soil surface (Figure 11). Soil temperature at 2 cm depth increased 12.8ºC with each additional T acre^{-1} of fuel load burned, while soil temperature at 4 cm depth only increased 2.5ºC with each additional T acre^{-1} of fuel load burned.

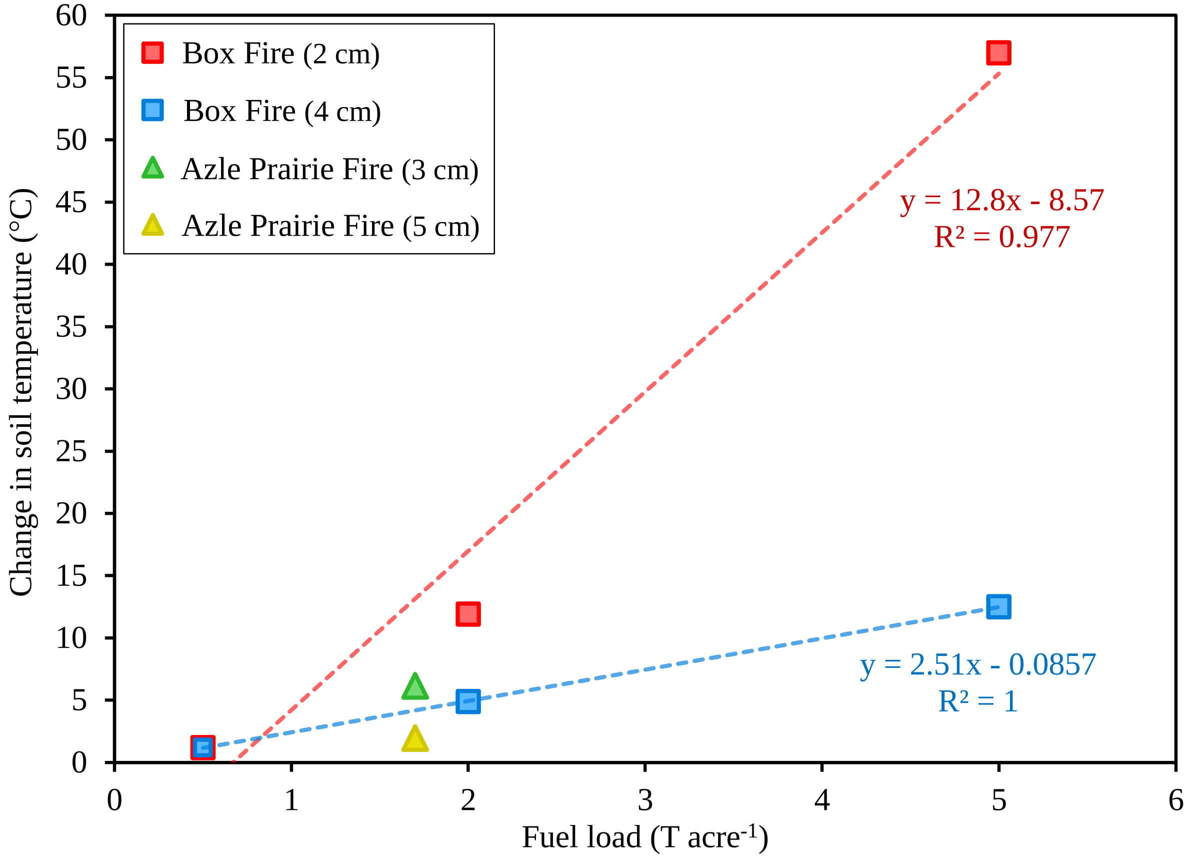

Figure 11. Change in soil temperature during fire. Standard curves relate fuel load to change in soil temperature reached within 25 minutes after ignition of the Box Fire. Changes in soil temperature achieved during the Azle Prairie Fire are also plotted.

Following fire, the 5 T acre^{-1} box was the only burn to cause a prolonged increase in soil temperature at 2 cm depth when compared to the ambient air temperature (Figures 12 and 13). Soil temperature at 2 cm depth was fairly consistent with ambient air temperatures following all other burns during the first week post-fire.

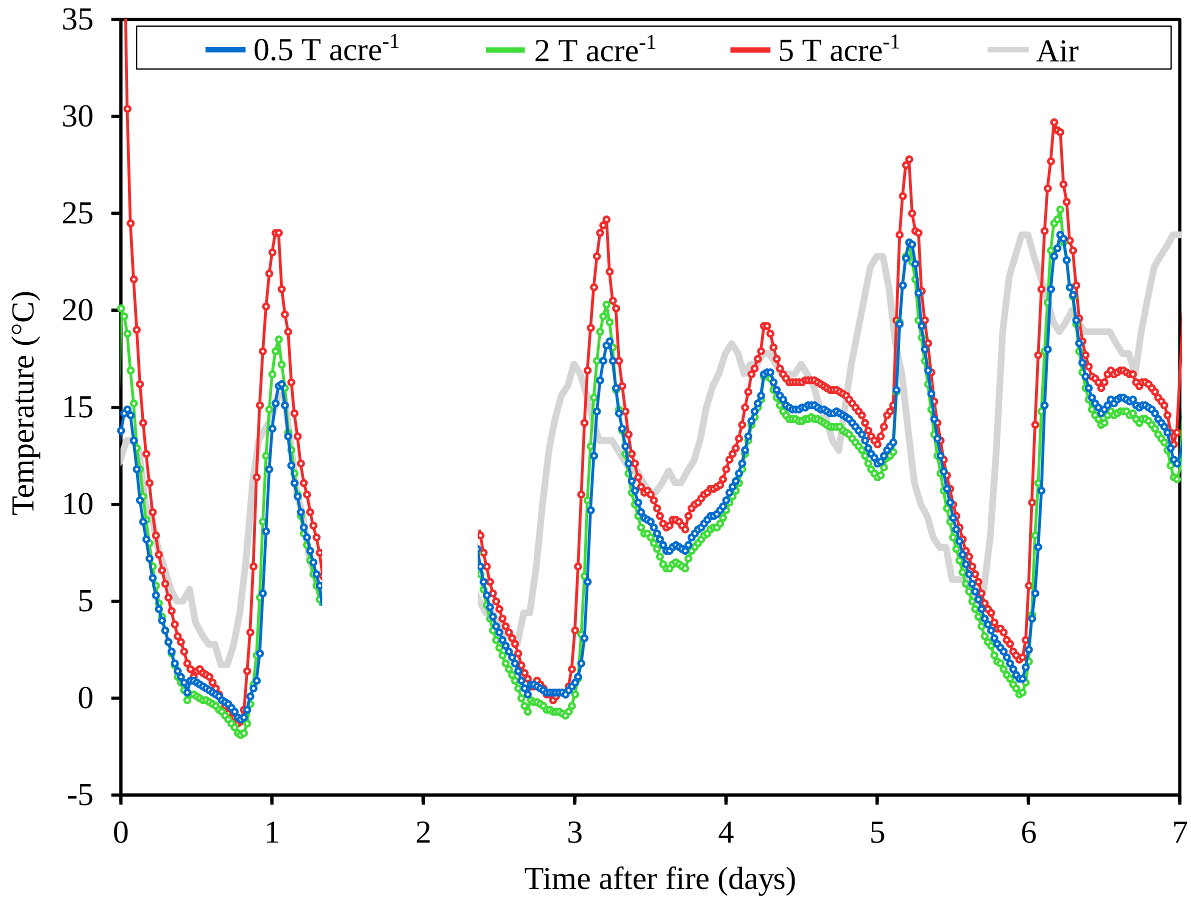

Figure 12. Soil temperature at 2 cm depth (30-minute intervals) and ambient air temperature (1-hour intervals) during the first week following the Box Fire. Air temperature data was downloaded from the weather station at the Naval Air Station Fort Worth Joint Reserve Base, approximately 7.4 km from the Box Fire. Gaps are due to incomplete data (data loggers lost battery power during the second day post-fire). Boxes were covered during fourth day post-fire.

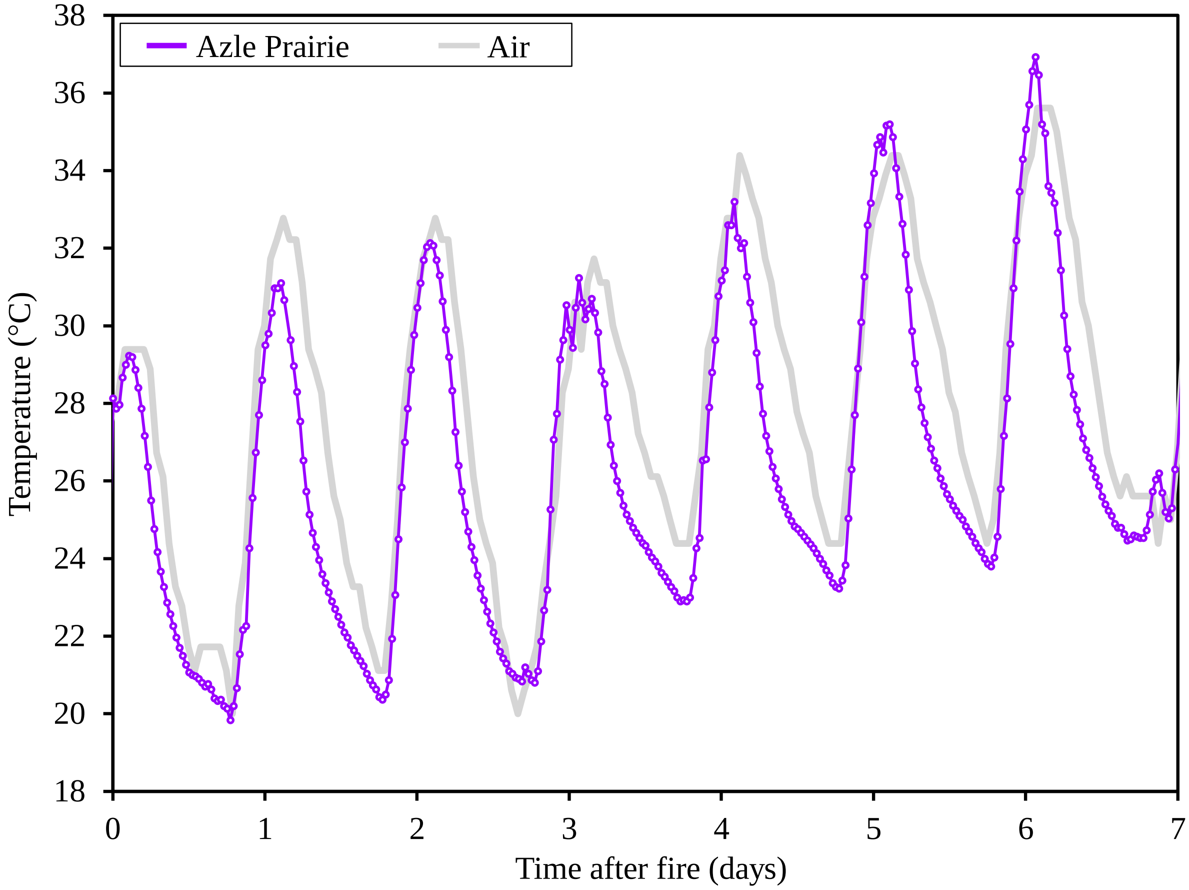

Figure 13. Soil temperature at 3 cm depth (30-minute intervals) and ambient air temperature (1-hour intervals) during the first week following the Azle Prairie Fire. Air temperature data was downloaded from the weather station at the Naval Air Station Fort Worth Joint Reserve Base, approximately 19.3 km from the Azle Prairie Fire.

Moisture content

Changes in soil moisture content at 4 cm depth were relatively small during fires, with the greatest change being just 0.7% (Figure 14). The 0.5 T acre^{-1} burn caused a small decrease in soil moisture content during fire. The 2 and 5 T acre^{-1} burns caused a short-term increase in soil moisture content during fire, followed by subsequent drying. This increase in soil moisture content was related to the fuel load burned, with the pulse in soil moisture content during fire increasing by 0.16% with each additional T acre^{-1} of fuel load burned (Figure 15). This temporary increase in soil moisture was not achieved during the Azle Prairie Fire, as soil moisture content remained stable.

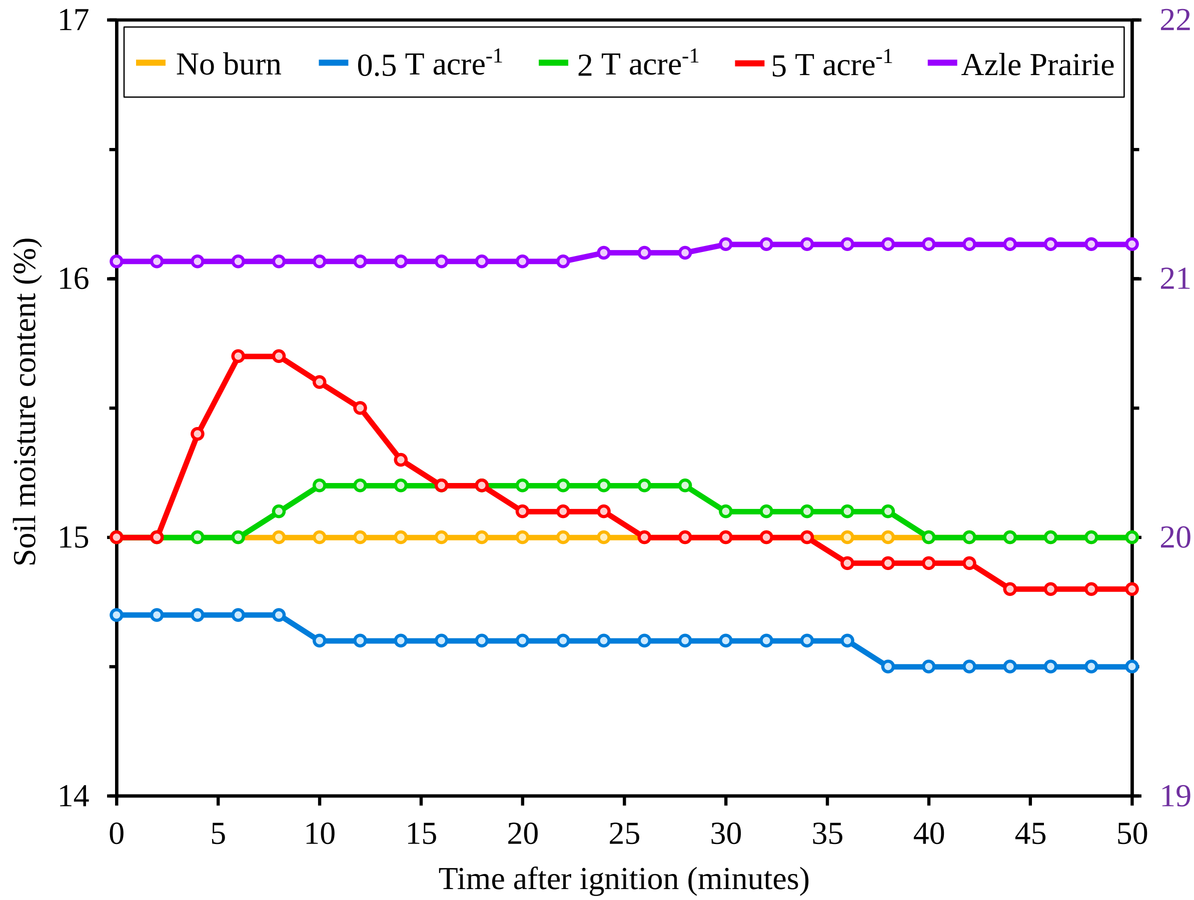

Figure 14. Soil moisture content during fires. Measurements taken at 2-minute intervals from SM300 sensors during burns and SM200 sensors in the unburned box. Sensors were buried at 4 cm depth during the Box Fire and 5 cm depth during the Azle Prairie Fire. The secondary vertical axis represents soil moisture content values for the Azle Prairie Fire.

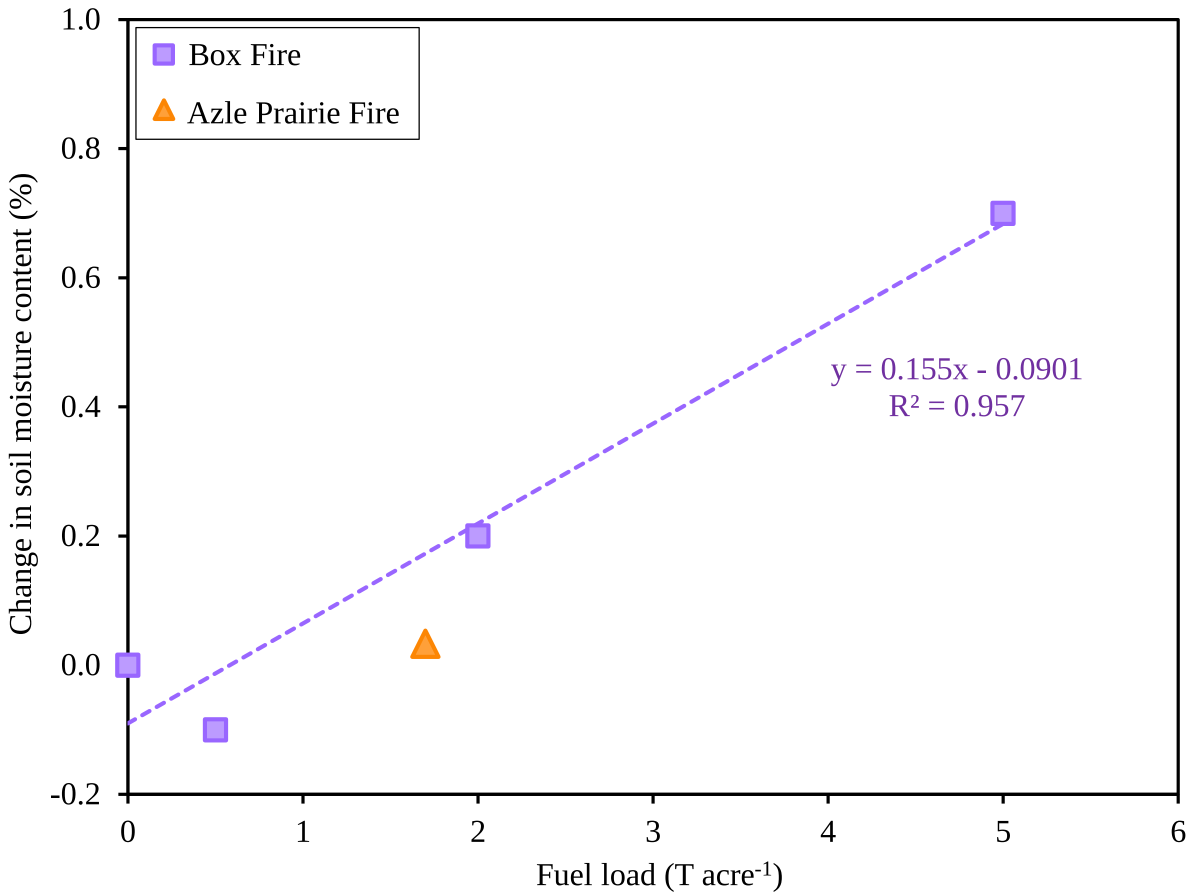

Figure 15. Change in soil moisture content during fire. Standard curve relates fuel load to change in soil moisture content at 4 cm depth reached within 25 minutes after ignition of the Box Fire. Change in soil moisture content during the Azle Prairie Fire (5 cm depth) is also plotted.

The greatest change in surface soil moisture content (0 - 2 cm depth) following the Box Fire occurred during the first two days post-fire (Figure 16). The 5 T acre^{-1} box lost 3.3% of its surface soil moisture content by the end of the first week post-fire, losing 2.6% soil moisture content within the first two days post-fire. During the first week post-fire, surface soil moisture content in the 0.5 and 2 T acre^{-1} boxes followed trends similar to the unburned box.

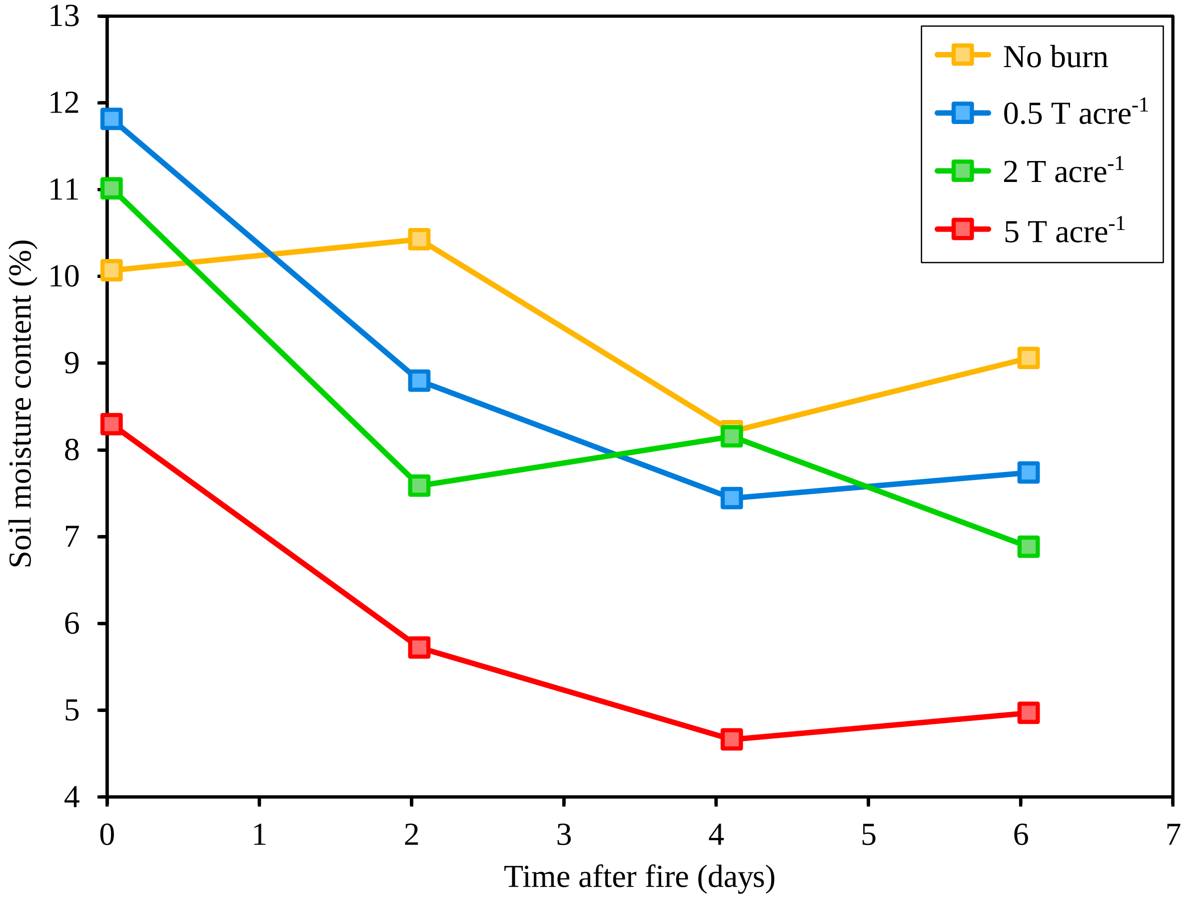

Figure 16. Surface soil moisture content following the Box Fire. Three representative samples taken from the surface 2 cm in each box were averaged at each sampling point.

Soil moisture content at 4 cm depth noticeably decreased during the first week post-fire only in the 5 T acre^{-1} box, experiencing a loss of 6.6% soil moisture content (Figure 17). Most of this loss of soil moisture occurred during the second half of the first week post-fire. While the Azle Prairie Fire did not include an unburned sample of soil moisture, the response in soil moisture content following this burn followed a similar trend to the unburned box.

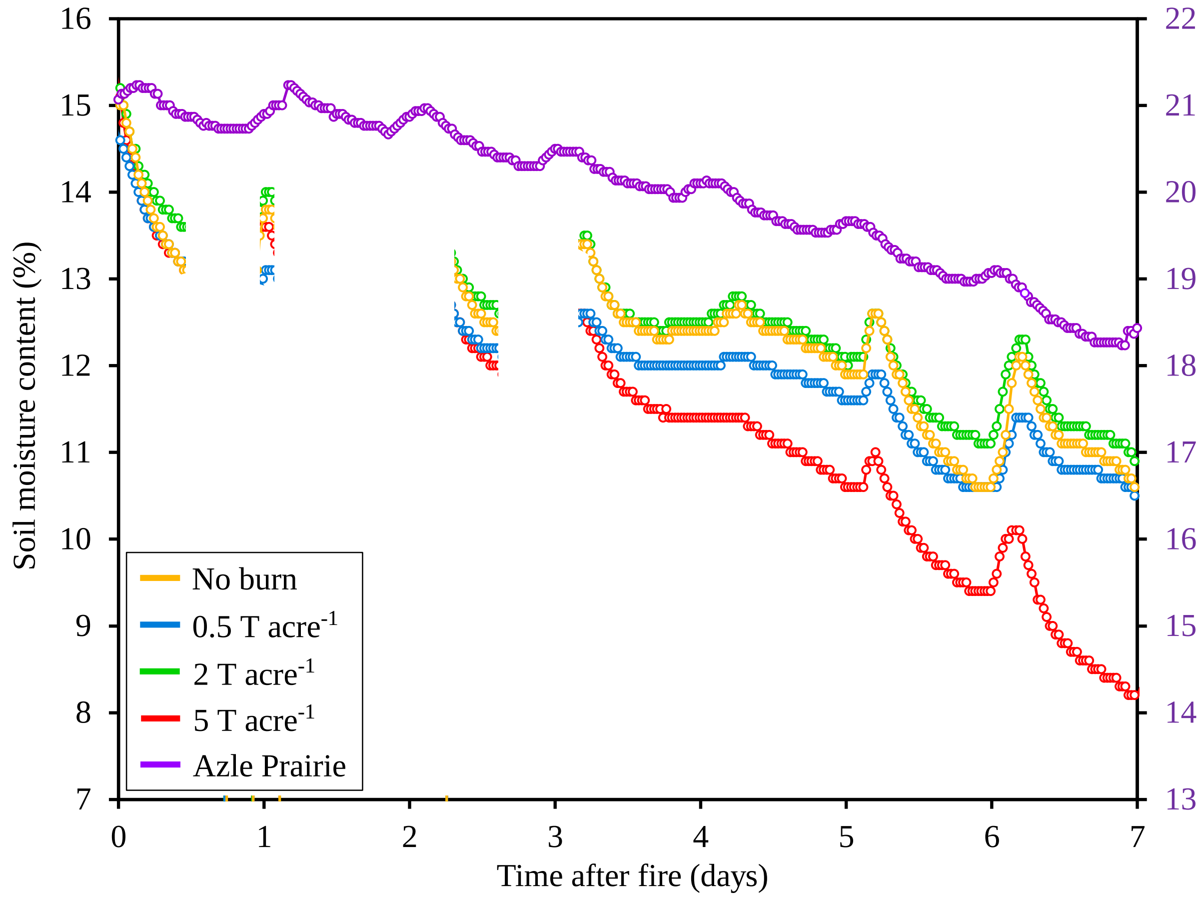

Figure 17. Soil moisture content following the Box Fire (4 cm depth) and Azle Prairie Fire (5 cm depth). Gaps are due to incomplete data (data loggers lost battery power during the second day post-fire). The secondary vertical axis represents soil moisture content values for the Azle Prairie Fire. Boxes were covered during the fourth day post-fire.

Water potential

Changes in soil water potential at 4 cm depth were relatively small during the Box Fire, following similar trends to changes in soil moisture content (Figure 18). The 5 and 2 T acre^{-1} fires caused a short-term increase in soil water potential during fire. This response in water potential was also related to the fuel load burned; with each additional T acre^{-1} of fuel burned, the pulse in water potential during fire increased by 0.66 kPa (Figure 19). No change in water potential was observed in the 0.5 T acre^{-1} or unburned boxes during fire.

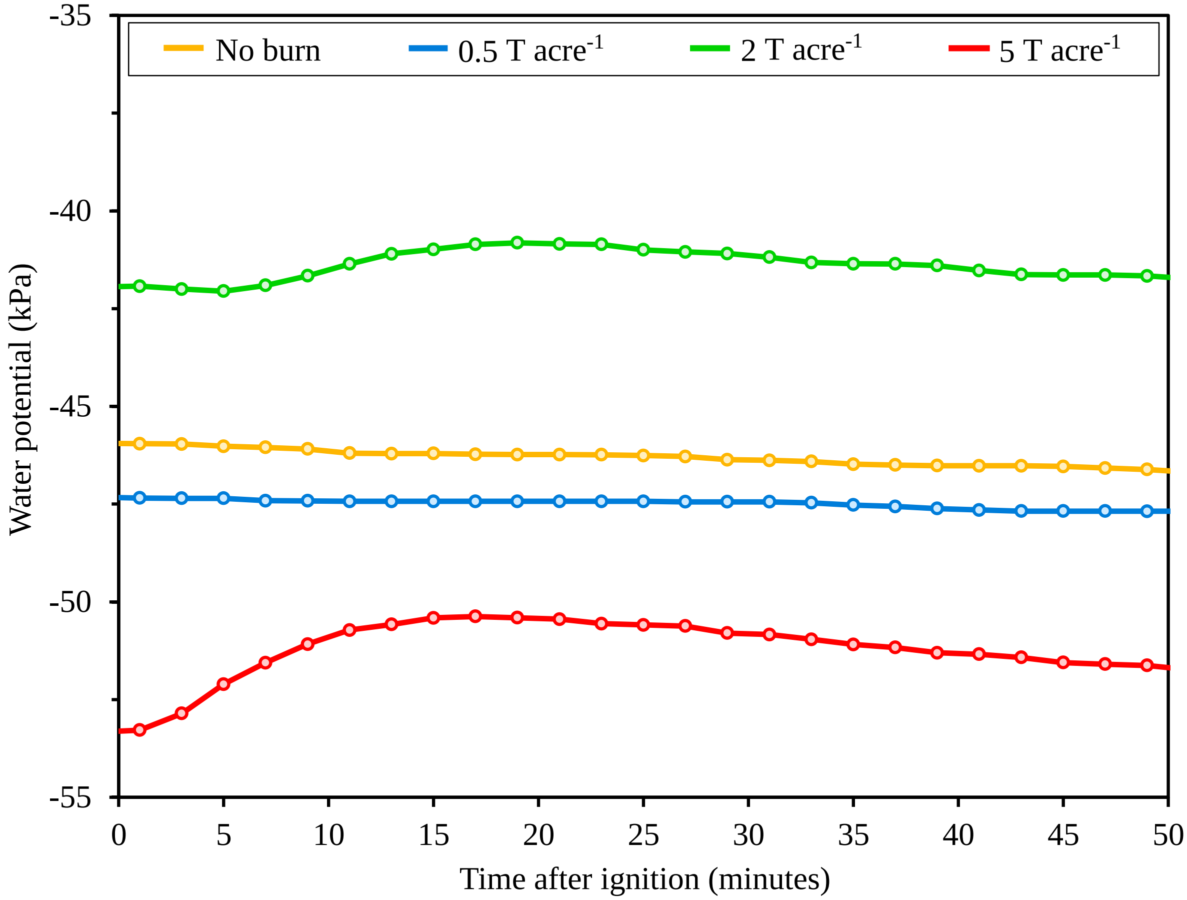

Figure 18. Soil water potential during the Box Fire. Measurements taken at 2-minute intervals from EQ2 equitensiometers buried at 4 cm depth.

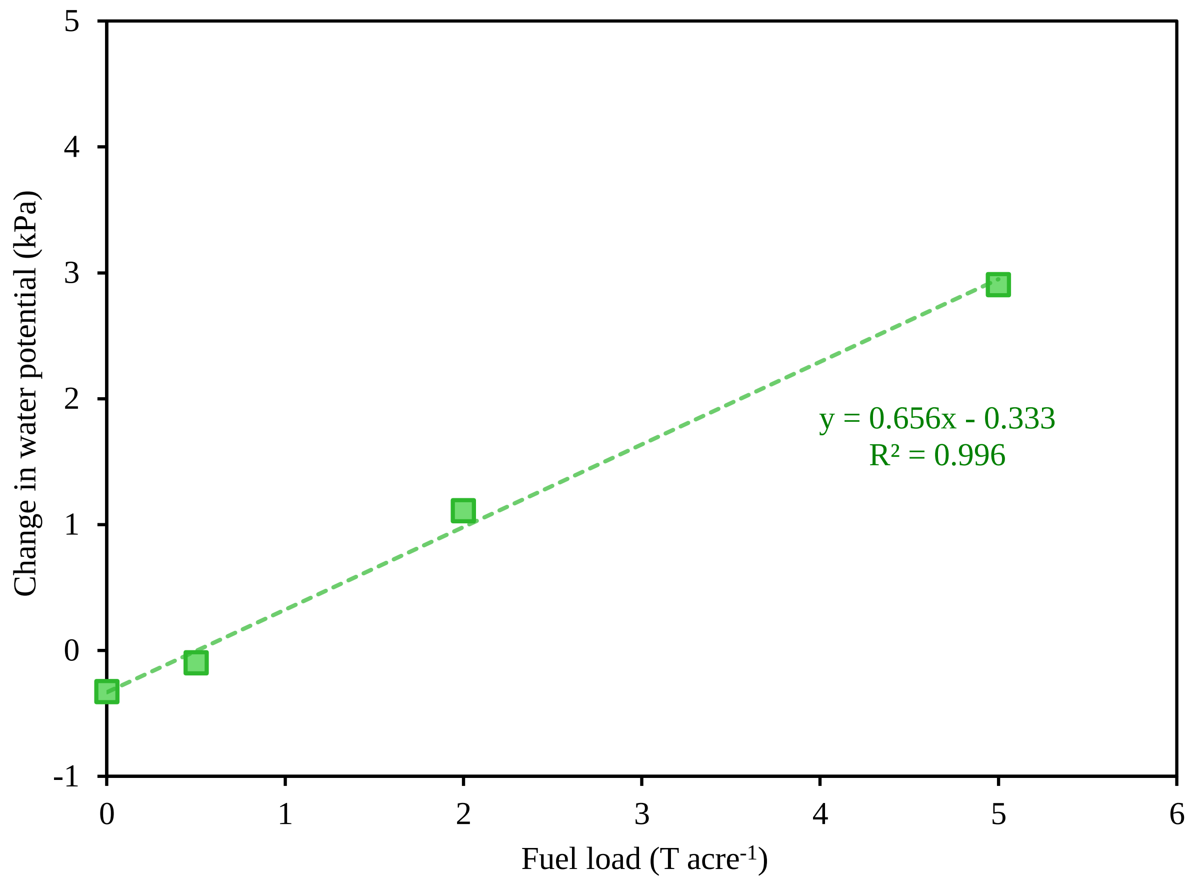

Figure 19. Change in soil water potential during fire. Standard curve relates fuel load to change in soil water potential at 4 cm depth reached within 25 minutes after ignition of the Box Fire.

During the first week following the Box Fire, water potential in the 0.5 T acre^{-1} box followed a similar trend to the unburned box (Figure 20). However, the 2 and 5 T acre^{-1} fires caused a decrease in water potential during the first week post-fire. The 5 T acre^{-1} burn caused a reduction in water potential of 14.6 kPa within the first two days post-fire, and a reduction of 47.2 kPa after the first week post-fire. The 2 T acre^{-1} burn caused a less prominent change in water potential within the first two days post-fire (8.1 kPa), but water potential in this box also reduced by 42.4 kPa by the end of the first week post-fire. This decrease in water potential is consistent with the loss of soil moisture observed in the 5 T acre^{-1} box during the first week post-fire.

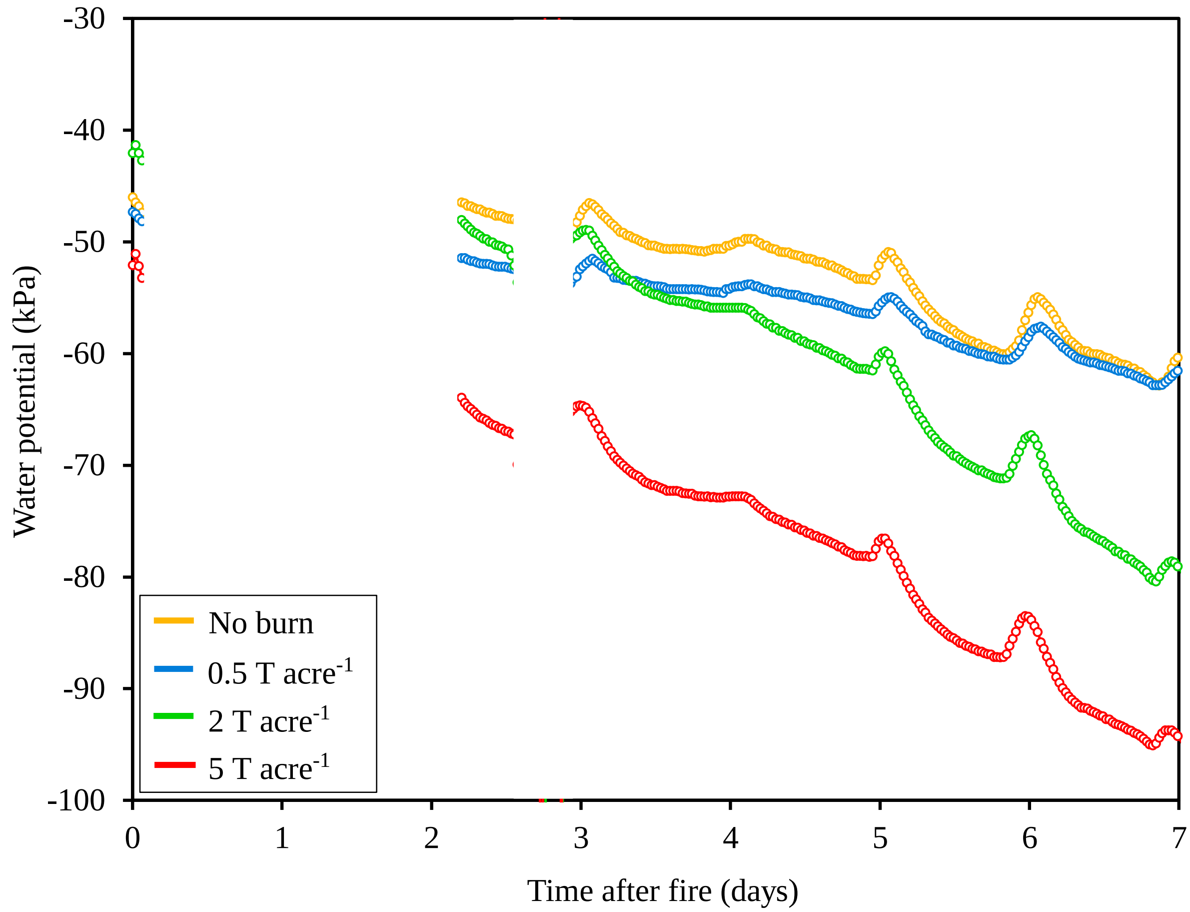

Figure 20. Soil water potential at 4 cm depth following the Box Fire. Gaps are due to incomplete data (data loggers lost battery power during the second day post-fire). Boxes were covered during the fourth day post-fire.

Infiltration capacity

There was no change in infiltration capacity in the unburned box following the Box Fire, and infiltration capacity decreased by 49.2 mm hr^{-1} following the 0.5 T $acre^{-1}$ fire (Figure 21). However, the 2 and 5 T $acre^{-1}$ burns resulted in a post-fire increase in infiltration capacity of 132.0 and 153.6 mm hr^{-1}, respectively. There was also an increase in infiltration capacity following the Azle Prairie Fire (54 mm hr^{-1}), but this change in infiltration capacity was less pronounced compared to the 2 and 5 T $acre^{-1}$ burns.

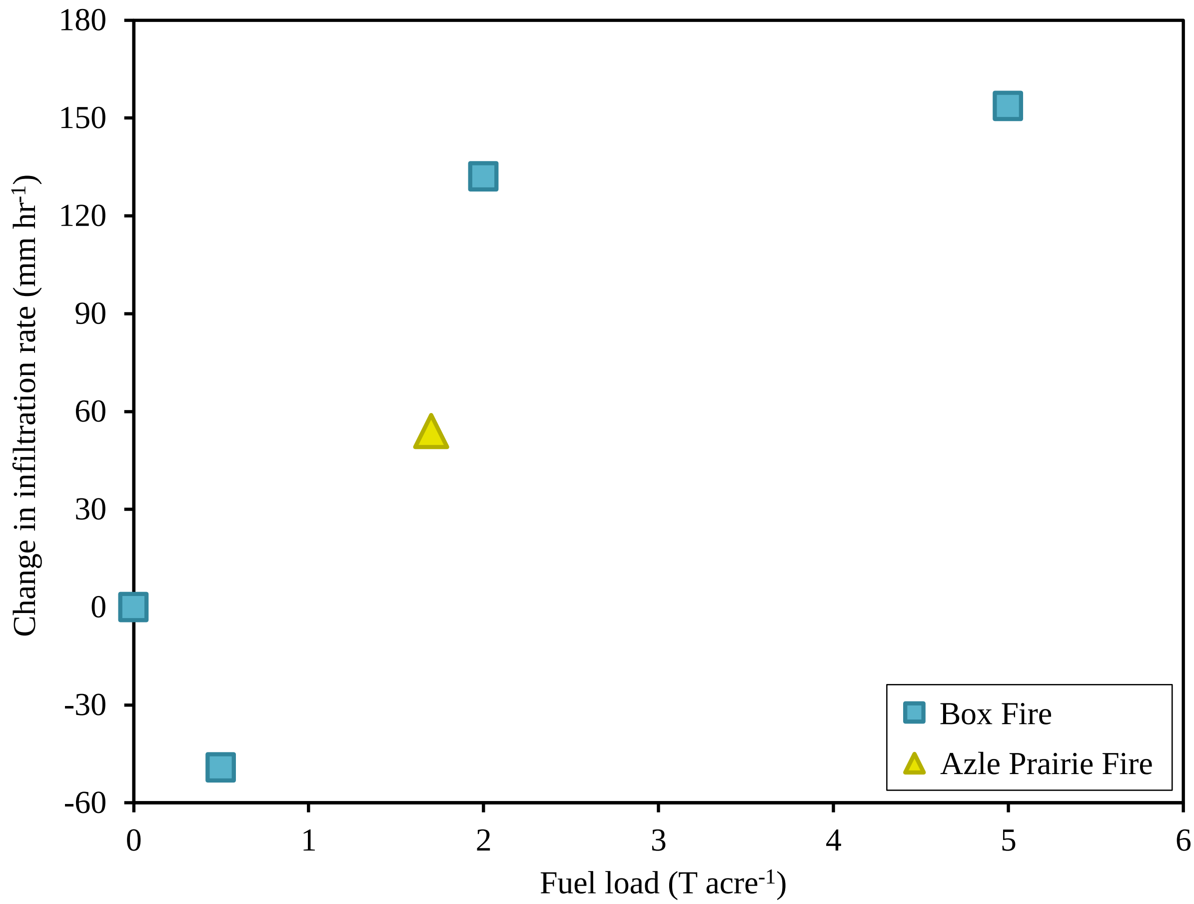

Figure 21. Change in infiltration capacity measured immediately pre- and post-fire.

Aggregate stability

Aggregate stability was relatively unchanged following the 0.5 T acre^{-1} fire as well as in the unburned box (Figure 22). However, the 2 and 5 T acre^{-1} burns caused a 16.8 and 13.0% decrease in aggregate stability, respectively.

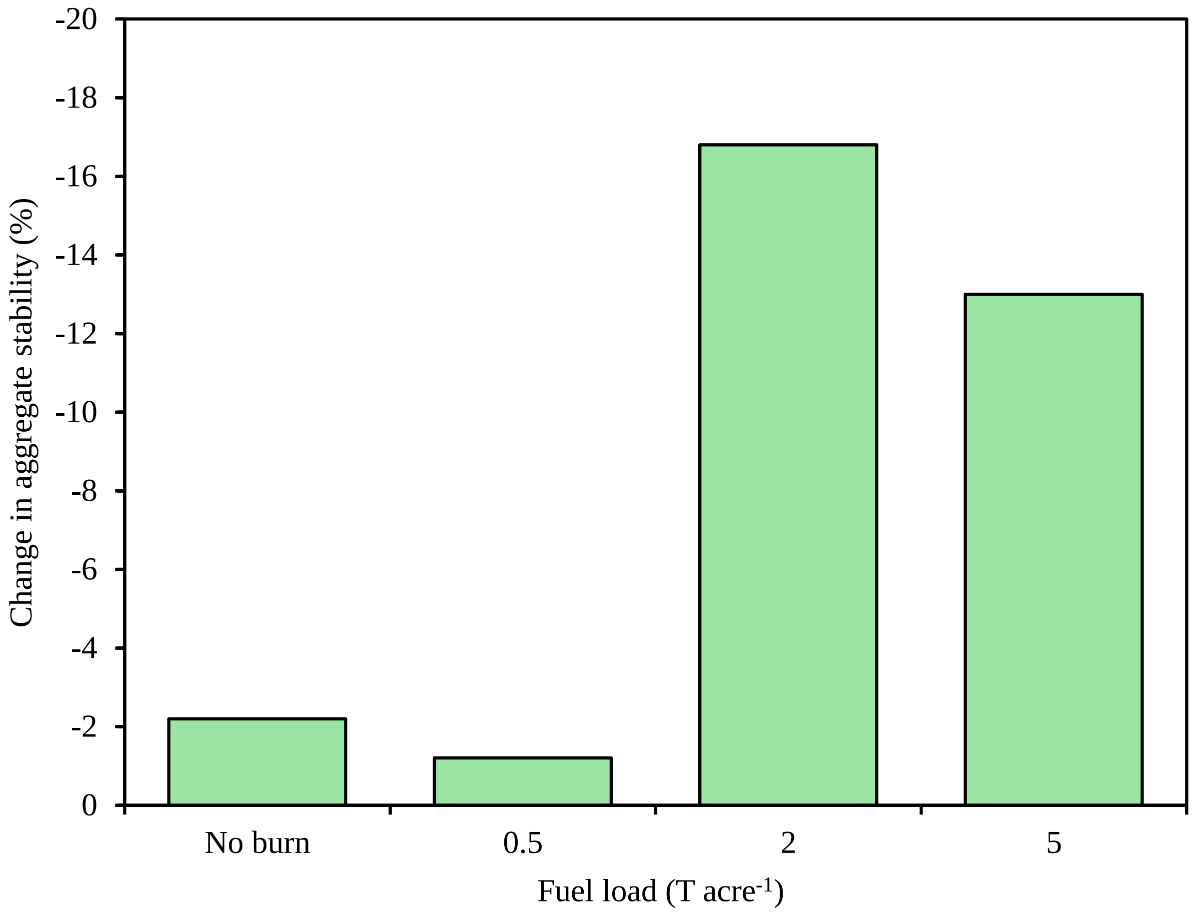

Figure 22. Change in aggregate stability measured immediately pre- and post-burn at the Box Fire.

Discussion

The results reported here confirm that increases in soil temperature during fire are essentially confined to the upper 2 to 3 cm of the soil profile, confirming previous research on near-surface temperature dynamics during fire (e.g., Busse et al. 2010). These results are also consistent with studies that have shown increases in soil temperature during fire are typically not sufficient to damage plant structures at depths greater than 7.6 cm (Beadle 1940). In addition, the maintained increase in soil temperature at greater depths during fire observed in this study was also documented by Bradstock and Auld (1995). Because increases in soil temperature are limited to the top few centimeters in the soil profile, impacts on vegetation will likely be greatest in annuals and other vegetative species with shallow root structures (Hatten et al. 2012). The increase in soil temperature during fire tends to follow a consistent relationship with the amount of fuel burned, with higher fuel loads causing greater increases in near-surface soil temperature.

The consistent heightened soil temperature at 2 cm depth compared to the ambient air temperature following the 5 T acre^{-1} fire and the lower water potential and moisture content in the 2 and 5 T acre^{-1} boxes one week post-burn may be due to lower albedo at the soil surface. Because the soil surface was much darker in these two boxes than the 0.5 T acre^{-1} and unburned boxes following the Box Fire, the 2 and 5 T acre^{-1} boxes likely absorbed more solar radiation, causing the soil to retain more heat and, therefore, lose more moisture. Soil temperatures 11ºC greater than pre-fire ambient soil temperatures have been recorded 5 days after prescribed fires (Preisler, Haase, and Sackett 2000).

The changes in soil temperature achieved during the Azle Prairie Fire were not as intense as would be predicted from the results of the Box Fire. This inconsistency is most likely due to greater fuel moisture, greater overall soil moisture content, burying the sensors at slightly greater depths during the Azle Prairie Fire (3 and 5 cm) compared to the Box Fire (2 and 4 cm), and, possibly, greater soil density in the field. Because higher soil moisture content restricts increases in soil temperature during fire (Frandsen and Ryan 1986), it is reasonable that field conditions during the Azle Prairie Fire would not achieve changes in soil temperature of similar magnitude to those observed during the Box Fire.

Increases in soil moisture content similar to those observed during the Box Fire were modeled in the soil heating experiment conducted by Massman (2015). The increase in soil moisture content was most pronounced in the 5 T acre^{-1} box and is likely caused by a change in water potential during fire, driving moisture downwards temporarily. Because this change in soil moisture content was not seen during the Azle Prairie Fire and only a minor change was detected in the 2 T acre^{-1} box, fuel loads less than 2 T acre^{-1} may not cause this change in soil moisture content during fire. Similar to the model produced by Massman (2015), all burns resulted in a loss of soil moisture content during the first week post-fire.

The prolonged increase in soil temperature and potential for higher soil moisture content following burns due to a reduction in transpiration may extend the growing season. These changes were shown to be limited to the surface 7.5 cm in the soil profile (Hatten et al. 2012). Post-fire increase in soil moisture content may also temporarily contribute to the recharge of aquifers prior to vegetative succession (Cardenas and Kanarek 2014).

Although the standard curves for changes in soil temperature, moisture content, and water potential created in this study use only a single soil type, similar changes would be expected to occur during prescribed fires conducted in other soils. While sandy soils may be expected to only experience minor changes in soil moisture content and temperature due their high infiltration capacity (Vermeire et al. 2005), soil texture was found to have little impact on soil temperatures reached during fire (Busse et al. 2010). Further research should examine how fires alter soil physical properties differently in various soil types to confirm the validity of our conclusions in different soils. Studies should also examine changes in soil moisture content during burns conducted in various soil types because post-fire changes in soil-water dynamics have been found to be inconsistent with grain size (Busse et al. 2005; Cardenas and Kanarek 2014).

Several studies have found a post-fire reduction in infiltration capacity due to water repellent layers beneath the soil surface (DeBano 2000; Doerr et al. 2006; Nyman et al. 2014). These circumstances are most common following severe fires (Ryan and Noste 1985). However, similar to this study, infiltration capacity has also been shown to increase following fire due to the "creation of water-retaining pores" (Shakesby and Doerr 2006, 276). The decrease in infiltration capacity following the 0.5 T $acre^{-1}$ burn as well as the increase in infiltration capacity following the 2 T $acre^{-1}$, 5 T $acre^{-1}$, and Azle Prairie Fire suggest that low severity burns capable of producing char on the soil surface may facilitate a post-fire increase in infiltration capacity. Fire-induced impacts on infiltration capacity are difficult to predict due to the mosaic produced by prescribed burns and differences specific to field sites (Penman et al. 2007).

The decrease in aggregate stability following the 2 and 5 T $acre^{-1}$ burns is consistent with other studies that examined changes in aggregate stability following wildfires. Severe fires were shown to affect aggregate stability in the top 5 cm of the soil profile, potentially resulting in greater soil erosion during the first four months post-fire (Andreu, Imeson, and Rubio 2001). Grassland fires were shown to have limited impacts on soil structure, while greater damage to surface soil may occur if shrubs or timber are burned (Ryan and Noste 1985; Iverson and Hutchinson 2002). Because the native grasses burned in the Box Fire resulted in a reduction in aggregate stability following the 2 and 5 T $acre^{-1}$ burns, high fuel loads of fine vegetation may also contribute to increased soil erosion and sediment transport.

When planning and conducting prescribed fires, land management should take into account the desired outcomes of burns and potential side effects of this land management technique. Standard curves for soil temperature during fire created in this study indicate that fuel loads greater than 4.2 T $acre^{-1}$ should be burned to achieve soil temperatures greater than 60ºC at 2 cm depth. Because soil temperatures must remain above this threshold and reach root structures to sufficiently kill invasive vegetation, burns aimed to remove vegetative species should be conducted in fuel loads greater than 4.2 T $acre^{-1}$ (Bradstock and Auld 1995; Preisler, Haase, and Sackett 2000). Root depth, fuel moisture, and soil moisture content should also be taken into account prior to these burns to determine the likelihood of achieving desired temperatures in the soil profile. However, this study also demonstrated that fuel loads greater than 2 T $acre^{-1}$ may decrease aggregate stability, thereby increasing the risk of soil erosion and sediment transport. Therefore, burns conducted at higher fuel loads may need to plan for post-fire erosion control in sensitive areas.

Because soil moisture content and infiltration capacity have high spatial variability following fire (Penman et al. 2007; Raison 1979; Robichaud 2000; Shakesby et al. 2003), further research should be conducted to confirm the results of this study in different soil types, fuel settings, and several areas within the same burn unit. In order to remove confounding variables that interact with soil-water dynamics, the soil used for the Box Fire was sieved and the bulk density was fairly consistent among all boxes. However, because soil temperature and moisture dynamics during and following fires can have high spatial variability even on small scales (Carrington 2010), the small sample sizes used in this study should be extrapolated to other locations with caution and further analysis of site characteristics.

While this study examined short-term effects of prescribed fire, further research is also needed to assess the long-term impacts prescribed fires have on soil-water dynamics following burns conducted at various ignition intervals (Boerner, Brinkman, and Sutherland

2004; Forgeard and Frenot 1996; Grilz and Romo 1994; Hatten et al. 2012; Uribe et al. 2013). This research should focus on fire-induced impacts on soil-water dynamics at the watershed and ecosystem scale, as these have been largely unexplored (DeBano 2000). Because post-fire vegetative recovery may take several years, long-term monitoring of burned sites is necessary to ensure prescribed fires achieve the intended land management goals with limited adverse effects on the environment (Blank, Chambers, and Zamudio 2003; Redmann et al. 1993). The field methods implemented in this study can be used to develop long-term fire monitoring programs to assist land management in planning for and monitoring the effects of prescribed fires.

Conclusion

This study monitored changes in soil physical properties (temperature, moisture content, water potential, infiltration capacity, and aggregate stability) during prescribed fires conducted at the following fuel loads: 0.5, 1.7, 2, and 5 T acre^{-1}. While burns at fuel loads less than 2 T acre^{-1} caused small changes in soil moisture content and water potential, burns conducted at fuel loads greater than 5 T acre^{-1} may reduce soil moisture content and prolong temperature increases in near-surface soil. Burns aimed to remove invasive vegetation should be conducted at fuel loads greater than 4.2 T acre^{-1} to achieve the 60ºC threshold for root mortality. However, burns greater than 2 T acre^{-1} were also shown to decrease aggregate stability; therefore, land management may need to plan for erosion control in these burn situations.

References

Andreu, V., A.C. Imeson, and J.L. Rubio. 2001. “Temporal changes in soil aggregates and water erosion after a wildfire in a Mediterranean pine forest.” *Catena* 44 (1): 69-84. doi:10.1016/S0341-8162(00)00177-6

Aston, A.R. and A.M. Gill. 1976. “Coupled soil moisture, heat and water vapour transfers under simulated fire conditions.” *Australian Journal of Soil Research* 14 (1): 55-66. doi:10.1071/SR9760055

Beadle, N.C.W. 1940. “Soil temperatures during forest fires and their effect on the survival of vegetation.” *Journal of Ecology* 28 (1): 180-192. doi:10.2307/2256168

Blank, R.R., J.C. Chambers, and D. Zamudio. 2003. “Restoring riparian corridors with fire: Effects on soil and vegetation.” *Range Management* 56 (4): 388-396. http://www.jstor.org/stable/4004044.

Boerner, R.E.J., A.T. Coates, D.A. Yaussy, and T.A. Waldrop. 2008. “Assessing ecosystem restoration alternatives in eastern deciduous forests: The view from belowground.” *Restoration Ecology* 16 (3): 425-434. doi:10.1111/j.1526-100X.2007.00312.x

Boerner, R.E.J., J.A. Brinkman, and E.K. Sutherland. 2004. “Effects of fire at two frequencies on nitrogen transformations and soil chemistry in a nitrogen-enriched forest landscape.” *Canadian Journal of Forest Research* 34 (3): 609-618. doi:10.1139/X03-221

Bradstock, R.A. and T.D. Auld. 1995. “Soil Temperatures during experimental bushfires in relation to fire intensity: Consequences for legume germination and fire management in south-eastern Australia.” *Applied Ecology* 32 (1): 76-84. http://www.jstor.org/stable/2404417.

Britton, C.M., R.G. Clark, and F.A. Sneva. 1983. “Effects of soil moisture on burned and clipped Idaho fescue.” *Range Management* 36 (6): 708-710. http://www.jstor.org/stable/3898191.

Busse, M.D., C.J. Shestak, K.R. Hubbert, and E.E. Knapp. 2010. “Soil physical properties regulate lethal heating during burning of woody residues.” *Soil Science Society of America Journal* 74 (3): 947-955. doi:10.2136/sssaj2009.0322

Busse, M.D., K.R. Hubbert, G.O. Fiddler, C.J. Shestak, and R.F. Powers. 2005. “Lethal soil temperatures during burning of masticated forest residues.” *International Journal of Wildland Fire* 14 (3): 267-276. doi:10.1071/WF04062

Cardenas, M.B. and M.R. Kanarek. 2014. “Soil moisture variation and dynamics across a wildfire burn boundary in a loblolly pine (*Pinus taeda*) forest.” *Journal of Hydrology* 519 (27): 490-502. doi:10.1016/j.jhydrol.2014.07.016

Carrington, M.E. 2010. "Effects of soil temperature during fire on seed survival in Florida sand pine scrub." *International Journal of Forestry Research*. Article ID 402346. doi:10.1155/2010/402346

Certini, G. 2005. "Effects of fire on properties of forest soils: A review." *Oecologia* 143 (1): 1-10. doi:10.1007/s00442-004-1788-8

Choczynska, J. and E.A. Johnson. 2009. "A soil heat and water transfer model to predict belowground grass rhizome bud death in a grass fire." *Journal of Vegetation Science* 20 (2): 277-287. doi:10.1111/j.1654-1103.2009.05757.x

Country Fire Authority. 2014. "Grassland curing field card." Edition 4. Accessed March 22, 2016. http://www.cfa.vic.gov.au/fm_files/attachments/publications/fieldcard.pdf.

DeBano, L.F. 2000. "The role of fire and soil heating on water repellency in wildland environments: A review." *Journal of Hydrology* 231 (1): 195-206. doi:10.1016/S0022-1694(00)00194-3

DeBano, L.F. and J.S. Krammes. 1966. "Water repellent soils and their relation to wildfire temperatures." *International Association of Scientific Hydrology* 11 (2): 14-19. doi:10.1080/02626666609493457

Doerr, S.H., R.A. Shakesby, and R.P.D. Walsh. 2000. "Soil water repellency: Its causes, characteristics and hydro-geomorphological significance." *Earth-Science Reviews* 51 (1): 33-65. doi:10.1016/S0012-8252(00)00011-8

Doerr, S.H., R.A. Shakesby, W.H. Blake, C.J. Chafer, G.S. Humphreys, and P.J. Wallbrink. 2006. "Effects of differing wildfire severities on soil wettability and implications for hydrological response." *Journal of Hydrology* 319 (1): 295-311. doi:10.1016/j.jhydrol.2005.06.038

Ebel, B.A. 2013. "Simulated unsaturated flow process after wildfire and interactions with slope aspect." *Water Resources Research* 49 (12): 8090-8107. doi:10.1002/2013WR014129

Fernandes, P.M. and H.S. Botelho. 2003. "A review of prescribed burning effectiveness in fire hazard reduction." *International Journal of Wildland Fire* 12 (2): 117-128. doi:10.1071/WF02042

Forgeard, F. and Y. Frenot. 1996. "Effects of burning on heathland soil chemical properties: An experimental study on the effect of heating and ash deposits." *Applied Ecology* 33 (4): 803-811. http://www.jstor.org/stable/2404950.

Frandsen, W.H. and K.C. Ryan. 1986. "Soil moisture reduces belowground heat flux and soil temperatures under a burning fuel pile." *Canadian Journal of Forest Research* 16 (2): 244-248. doi:10.1139/x86-043

Grace, J.B., L.K. Allain, H.Q. Baldwin, A.G. Billock, W.R. Eddleman, A.M. Given, C.W. Jeske, and R. Moss. 2005. "Effects of prescribed fire in the coastal prairies of Texas: USGS open file report 2005-1287." U.S. Geological Survey. http://www.nwrc.usgs.gov/factshts/2005-1287-fire-in-coastal-texas-report.pdf.

Grilz, P.L. and J.T. Romo. 1994. "Water relations and growth of *Bromus inermis* Leyss (smooth brome) following spring or autumn burning in a fescue prairie." *American Midland Naturalist* 132 (2): 340-348. http://www.jstor.org/stable/2426590.

Hatten, J., D. Zabowski, A. Ogden, W. Theis, and B. Choi. 2012. "Role of season and interval of prescribed burning on ponderosa pine growth in relation to soil inorganic N and P and moisture." *Forest Ecology and Management* 269: 106-115. doi:10.1016/j.foreco.2011.12.036

Hille, M.G. and S.L. Stephens. 2005. "Mixed conifer forest duff consumption during prescribed fires: Tree crown impacts." *Forest Science* 51 (5): 417-424. http://nature.berkeley.edu/stephenslab/wp-content/uploads/2015/04/Hille-Stephens-duff-FS-05.pdf.

Huang, J. and R.E.J. Boerner. 2008. "Shifts in morphological traits, seed production, and early establishment of *Desmodium nudiflorum* following prescribed fire, alone or in combination with forest canopy thinning." *Botany* 86 (4): 376-384. doi:10.1139/B08-006

Hutchinson, T.F., R.E.J. Boerner, S. Sutherland, E.K. Sutherland, M. Ortt, and L.R. Iverson. 2005. "Prescribed fire effects on the herbaceous layer of mixed-oak forests." *Canadian Journal of Forest Research* 35 (4): 877-890. doi:10.1139/X04-189

Iverson, L.R. and T.F. Hutchinson. 2002. "Soil temperature and moisture fluctuations during and after prescribed fire in mixed-oak forests, USA." *Natural Areas Journal* 22 (4): 296-304. http://www.treesearch.fs.fed.us/pubs/22433.

Knapp, E.E., B.L. Estes, and C.N. Skinner. 2009. "Ecological effects of prescribed fire season: A literature review and synthesis for managers." JFSP Synthesis Reports. Paper 4. http://digitalcommons.unl.edu/jfspsynthesis/4.

Le Bissonnais, Y. 1996. "Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology." *European Journal of Soil Science* 47 (4): 425-437. doi:10.1111/j.1365-2389.1996.tb01843.x

Lee, S., K. Baumann, J.J. Schauer, R.J. Sheesley, L.P. Naeher, S. Meinardi, D.R. Blake, E.S. Edgerton, A.G. Russell, and M. Clements. 2005. "Gaseous and particulate emissions from prescribed burning in Georgia." *Environmental Science and Technology* 39 (23): 9049-9056. doi:10.1021/es051583l

Massman, W.J. 2012. "Modeling soil heating and moisture transport under extreme conditions: Forest fires and slash pile burns." *Water Resources Research* 48 (10): W10548. doi:10.1029/2011WR011710

Massman, W.J. 2015. "A non-equilibrium model for soil heating and moisture transport during extreme surface heating: The soil (heat–moisture–vapor) HMV-model version 1." *Geoscientific Model Development* 8 (11): 3659-3680. doi:10.5194/gmd-8-3659-2015

Massman, W.J., J.M. Frank, and S.J. Mooney. 2010. "Advancing investigation and physical modeling of first-order fire effects in soils." *Fire Ecology* 6 (1): 36-54. doi:10.4996/fireecology.0601036

Melgoza, G., R.S. Nowak, and R.J. Tausch. 1990. "Soil water exploitation after fire: Competition between *Bromus tectorum* (cheatgrass) and two native species." *Oecologia* 83 (1): 7-13. http://www.jstor.org/stable/4219288.

Mullen, R.M., A.E. Springer, and T.E. Kolb. 2006. "Complex effects of prescribed fire on restoring the soil water content in a high-elevation riparian meadow, Arizona." *Restoration Ecology* 14 (2): 242-250. doi:10.1111/j.1526-100X.2006.00126.x

Natural Resources Conservation Service. 2014. "Soil Survey Geographic (SSURGO) Database for Upper West Fork Trinity Subbasin, Texas." United States Department of Agriculture. Accessed September 10, 2015. http://www.arcgis.com/apps/OnePane/basicviewer/index.html?appid=a23eb436f6ec4ad6982000dbaddea5ea.

Neary, D.G., C.C. Klopatek, L.F. DeBano, and P.F. Ffolliott. 1999. "Fire effects on belowground sustainability: A review and synthesis." *Forest Ecology and Management* 122 (1): 51-71. doi:10.1016/S0378-1127(99)00032-8

Nyman, P., G.J. Sheridan, H.G. Smith, and P.N.J. Lane. 2014. "Modeling the effects of surface storage, macropore flow, and water repellency on infiltration after wildfire." *Journal of Hydrology* 513: 301-313. doi:10.1016/j.jhydrol.2014.02.044

Ortmann, J., K.L. Miles, J.L. Stubbendieck, and W.H. Schacht. 1997. "G97-1319 Management of smooth sumac on grasslands." University of Nebraska-Lincoln Extension. Paper 1305. http://digitalcommons.unl.edu/extensionhist/1305.

Pelaez, D.V., R.M. Boo, M.D. Mayor, and O.R. Elia. 2001. "Effect of fire on perennial grasses in central semiarid Argentina." *Range Management* 54 (5): 617-621. http://www.jstor.org/stable/4003593.

Penman, T.D. and A.L. Towerton. 2008. "Soil temperatures during autumn prescribed burning: Implications for the germination of fire responsive species?" *International Journal of Wildland Fire* 17 (5): 572-578. doi:10.1071/WF07092

Penman, T.D., R.P. Kavanagh, D.L. Binns, and D.R. Melick. 2007. "Patchiness of prescribed burns in dry sclerophyll eucalypt forests in South-eastern Australia." *Forest Ecology and Management* 252 (1): 24-32. doi:10.1016/j.foreco.2007.06.004

Preisler, H.K., S.M. Haase, and S.S. Sackett. 2000. "Modeling and risk assessment for soil temperatures beneath prescribed forest fires." *Environmental and Ecological Statistics* 7 (3): 239-254. doi:10.1023/A:1009615032159

Raison, R.J. 1979. "Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: A review." *Plant and Soil* 51 (1): 73-108. doi:10.1007/BF02205929

Redmann, R.E. 1978. "Plant and soil water potentials following fire in a northern mixed grassland." *Range Management* 31 (6): 443-445. http://www.jstor.org/stable/3897203.

Redmann, R.E., J.T. Romo, B. Pylypec, and E.A. Driver. 1993. "Impacts of burning on primary productivity of *Festuca* and *Stipa-Agropyron* grasslands in central Saskatchewan." *American Midland Naturalist* 130 (2): 262-273. http://www.jstor.org/stable/2426126.

Robichaud, P.R. 2000. "Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain Forests, USA." *Journal of Hydrology* 231–232 (1): 220-229. http://www.treesearch.fs.fed.us/pubs/23562.

Romo, J.T., P.L. Grilz, R.E. Redmann, and E.A. Driver. 1993. "Standing crop, biomass allocation patterns, and soil-plant water relations in *Symphoricarpos occidentalis* Hook. following autumn or spring burning." *American Midland Naturalist* 130 (1): 106-115. www.jstor.org/stable/2426279.

Rubio, C.M., X. Úbeda, and F. Ferrer. 2012. "Response of the thermal conductivity as a function of water content of a burnt Mediterranean loam soil." *Open Journal of Soil Science* 2 (1): 1-6. doi:10.4236/ojss.2012.21001

Ryan, K.C., and N.V. Noste. 1985. "Evaluating prescribed fires." General Technical Report INT-182. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station. 230-238. http://www.fs.fed.us/rm/pubs/rmrs_gtr292/1985_ryan.pdf.

Savage, M.J. and K. Vermeulen. 1983. "Microclimate modification of tall moist grasslands of Natal by spring burning." *Range Management* 36 (2):172-174. http://www.jstor.org/stable/3898156.

Shakesby, R.A., C.J. Chafer, S.H. Doerr, W.H. Blake, P. Wallbrink, G.S. Humphreys, and B.A. Harrington. 2003. “Fire severity, water repellency characteristics, and hydrogeomorphological changes following the Christmas 2001 Sydney forest fires.” *Australian Geographer* 34 (2): 147-175. doi:10.1080/00049180301736

Shakesby, R.A. and S.H. Doerr. 2006. “Wildfire as a hydrological and geomorphological agent.” *Earth-Science Reviews* 74 (3): 269-307. doi:10.1016/j.earscirev.2005.10.006

Smith, D.M., D. Finch, C. Gunning, R. Jemison, and J.F. Kelly. 2009. “Post-wildfire recovery of riparian vegetation during a period of water scarcity in the southwestern USA.” *Fire Ecology* 5 (1): 38-55. doi:10.4996/fireecology.0501038

Stephens, S.L. and D.L. Fry. 2005. “Fire history in coast redwood stands in the northeastern Santa Cruz Mountains, California.” *Fire Ecology* 1 (1): 2-19. doi:10.4996/fireecology.0101002

Stoof, C.R., A.D. Kort, T.F.A. Bishop, D. Moore, J.G. Wesseling, and C.J. Ritsema. 2011a. “How rock fragments and moisture affect soil temperatures during fire.” *Soil Science Society of America Journal* 75 (3): 1133-1143. doi:10.2136/sssaj2010.0322

Stoof, C.R., D. Moore, C.J. Ritsema, and L.W. Dekker. 2011b. “Natural and fire-induced soil water repellency in a Portuguese shrubland.” *Soil Science Society of America Journal* 75 (6): 2283-2295. doi:10.2136/sssaj2011.0046

Teague, W.R., W.E. Grant, U.P. Kreuter, H. Diaz-Solis, S. Dube, M.M. Kothmann, W.E. Pinchak, and R.J. Ansley. 2008. “An ecological economic simulation model for assessing fire and grazing management effects on mesquite rangelands in Texas.” *Ecological Economics* 64 (3): 611-624. doi:10.1016/j.ecolecon.2007.04.010

Texas Natural Resources Information System. 2015. “Azle Quad Map - SE Quarter-Quad.” 2015 TOP 0.5M NC/CIR. Accessed March 4, 2016. https://tnris.org/data-download/#!/quad/Azle.

Thomas, P.B., E.C. Morris, T.D. Auld, and A.M. Haigh. 2010. “The interaction of temperature, water availability and fire cues regulates seed germination in a fire-prone landscape.” *Oecologia* 162 (2): 293-302. doi:10.1007/s00442-009-1456-0

Uribe, C., R. Inclán, D.M. Sánchez, M.A. Clavero, A.M. Fernández, R. Morante, A. Cardeña, A. Blanco, and H.V. Miegroet. 2013. “Effect of wildfires on soil respiration in three typical Mediterranean forest ecosystems in Madrid, Spain.” *Plant Soil* 369 (1): 403-420. doi:10.1007/s11104-012-1576-x

Valette, J.C., V. Gomendy, J. Marechal, C. Houssard, and D. Gillon. 1994. “Heat transfer in the soil during very low-intensity experimental fires: The role of duff and soil moisture content.” *International Journal of Wildland Fire* 4 (4): 225-237. doi:10.1071/WF9940225

Vega, J.A., C. Fernandez, and T. Fonturbel. 2005. “Throughfall, runoff and soil erosion after prescribed burning in gorse shrubland in Galicia (NW Spain).” *Land Degradation and Development* 16 (1): 37-51. doi:10.1002/ldr.643

Vermeire, L.T., D.B. Wester, R.B. Mitchell, and S.D. Fuhlendorf. 2005. “Fire and grazing effects on wind erosion, soil water content, and soil temperature.” *Environmental Quality* 34 (5): 1559-1565. doi:10.2134/jeq2005.0006

Vermeire, L.T., J.L. Crowder, and D.B. Wester. 2011. “Plant community and soil environment response to summer fire in the northern Great Plains.” *Rangeland Ecology and Management* 64 (1): 37-46. doi:10.2111/REM-D-10-00049.1

VITA

Personal Background
Erik R. Anderson
San Jose, California
Son of Gregg and Jeanine Anderson

Education
2009 Diploma, Bellarmine College Preparatory, San Jose, CA
2014 B.A. Marine Science, University of San Diego, San Diego, CA
2016 M.S. Environmental Science, Texas Christian University, Fort Worth, TX

Experience
2014 – 2016 Teaching Assistant, School of Geology, Energy, and the Environment, Texas Christian University

Summer 2013 Research Assistant, SDSU Coastal and Marine Institute Laboratory

Summer 2012 Research Assistant, Department of Environmental and Ocean Sciences, University of San Diego

Presentations
Anderson, E.R. 2016. "Quantifying physical changes in near-surface soil during prescribed fire." Michael and Sally McCracken Student Research Symposium. Texas Christian University. Fort Worth, TX.

Anderson, E.R. and M.C. Slattery. 2016. "Quantifying physical changes in near-surface soil during prescribed fire." American Association of Geographers Annual Meeting. San Francisco, CA.

Anderson, E.R. 2015. "Recent wildfire progression in the Sierra Nevada wildland-urban interface." Michael and Sally McCracken Student Research Symposium. Texas Christian University. Fort Worth, TX.

Anderson, E.R., A.M. Warneke, and J.D. Long. 2014. "Copper disrupts herbivore feeding preference." Creative Collaborations Undergraduate Research Conference. University of San Diego. San Diego, CA.

Awards
2015 Golden Key International Honour Society
2012 Mortar Board

ABSTRACT

QUANTIFYING PHYSICAL CHANGES IN
NEAR-SURFACE SOIL DURING PRESCRIBED FIRE

by Erik R. Anderson, M.S., 2016
School of Geology, Energy, and the Environment
Texas Christian University

Thesis Advisor: Michael Slattery, Professor & Director of Institute of Environmental Studies

Committee Members: Rob Denkhaus, Natural Resource Manager at FWNC&R

Tamie Morgan, Professor of Professional Practice

Prescribed fires are conducted to reduce accumulated fuel loads and maintain fire-dependent vegetative species and wildlife habitats. Few studies have examined the impacts prescribed fires have on near-surface soil-water dynamics. Fire-induced changes in soil temperature, moisture content, water potential, infiltration capacity, and aggregate stability were measured during experimental fires (fuel loads: 0.5, 2, and 5 T acre^{-1}) and a prescribed fire conducted in the field (1.7 T acre^{-1}). Burns at fuel loads less than 2 T acre^{-1} caused small changes in soil moisture content and water potential, while burns conducted at fuel loads greater than 5 T acre^{-1} may reduce soil moisture content and prolong increased temperature in near-surface soil. Burns aimed to remove invasive vegetation should be conducted at fuel loads greater than 4.2 T acre^{-1} to achieve the 60ºC threshold for root mortality; however, land management may need to plan for erosion control in these burn situations.