Fuel Moisture Changes from Sprinkler-watering Treatments in Interior Alaska Boreal Forests

by

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ABSTRACT

Key Words: Wildfire Prevention, Sprinkler Systems, and Fuel Moisture Content

This thesis studied the efficacy of sprinklers for fuel hazard reduction to prevent wildfires. Fire management's response capacity to suppress wildfires is increasingly becoming overwhelmed because of climate change and its effects on fire regimes. Sprinkler-watering can change fuel moisture around values at risk to either reduce fire intensity or prevent it entirely. Sprinkler systems have proven to be effective at preventing wildfires, making them worthwhile to research as potential firefighting apparatus.

The purpose of this research is to examine the effects of sprinkler-watering on fuel moisture changes in lowland boreal forests floors around interior Alaska. The experiment tested 6 sites, and each site contained 2 sprinkler-watering treatment levels and a control treatment. Treatment units consisted of 4 plots containing 4 temporal samples, which measured the amount of water received from sprinkler-watering and consequential change in fuel moisture content. These moss and upper-duff samples showed that amount of water distributed from sprinkler-watering caused a positive change in fuel moisture. The sprinkler-watering distribution was approximately 10 mm of equivalent rainfall per 3.8 L of gas. This experiment recommends moss and upper-duff receives 10 and 20 mm of equivalent rainfall to raise moisture beyond ignition for this sprinkler system.

A wildfire prevention strategy is safer for people and more cost-effective than fire suppression. Indirect response tactics namely fuel management, value engineering, and sprinkler protection could help prepare values for wildfires. Sprinkler protection can occur at the interface, community, and landscape levels to allow wildfires to burn around values at risk to restore ecological resilience.

PREFACE

This thesis is an original work by Devon Edward Barnes. However, written permission for use of Figures 2, 3, 8, and 31 in this document was sought from Canadian Interagency Forest Fire Centre (2016), Barnes *et al.* (2012) and Partners in Protection (2003). Microsoft Excel and R Studio software produced the analysis, and the data is stored electronically at the University of Alberta; contact the Western Partnership for Wildland Fire Science for release requests.

DEDICATION

I dedicate this thesis research to the fire crews who risk their own safety to protect people and property during wildfires.

ACKNOWLEDGEMENTS

I would like to thank John and Sue Barnes for encouraging me to pursue post-secondary learning, and John Anthony Barnes for helping me with the editing process. I believe that people are a product of their support systems, and this thesis would not have been possible without the continual support of Dr. Mike Flannigan and thesis committee members Greg Baxter, Dr. Mike Wotton and Dr. Glen Armstrong who provided ongoing and constructive review of its drafts. Colleagues at the University of Alberta's Western Partnership for Wildland Fire Science also offered many insightful perspectives that undoubtedly improved my learning experience, and in-kind assistance provided by the U.S. Bureau of Land Management's Alaska Fire Service made the field research possible. Many thanks are due to all of these people, and I would like to acknowledge their efforts in helping to support this thesis.

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ACRONYMS

ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
BUI	Build Up Index
CFFDRS	Canadian Forest Fire Danger Rating System
CWPP	Community Wildfire Protection Plan
DC	Drought Code
DMC	Duff Moisture Code
FFMC	Fine Fuel Moisture Code
FMP	Fire Management Plan
FWI	Canadian Fire Weather Index
ISI	Initial Spread Index
IMT	Incident Management Team
RAWS	Remotely Automated Weather Stations
Q-Q	Dataset one quartiles versus dataset two quartiles
WUI	Wildland Urban Interface

1 INTRODUCTION

Wildfire management is becoming overwhelmed; this thesis suggests that sprinkler protection can mitigate the increasing fire risk to prevent wildfires around values. A literature review reveals certain wildfire management pressures that can act as drivers for change in wildfire management practices. Sprinkler-watering prevents wildfires by wetting fuels to change their fuel moisture, thus mitigating fire behaviour or deter ignition. This research investigates sprinkler-watering effect on fuel moisture content with the intent of quantifying treatment levels. Once achieved, these levels can provide estimates as a means to reduce probability of ignition in lowland boreal forests in and around Fairbanks, Alaska.

1.1 Literature Review

The role of wildfire management is to limit exposure to wildfire risk by matching it with an appropriate response. Climate change is expected to continue to increase wildfire activity in the future (Running 2006), and this could be further exacerbated by wildfire exclusion policies, possibly risking catastrophic wildfires. Meanwhile, urban sprawl into fire-prone environments is leaving many fire agencies lacking the wildfire resources needed to meet the increased fire load. A logic diagram in Figure 1 shows wildfire management pressures that may drive a change in risk strategies and response tactics. Generally, wildfire risk is increasing because weather is becoming more conducive to wildfires (Wotton *et al*. 2010), and the stagnation of forests caused by fire exclusion policies. Meanwhile, wildfire agencies struggle to protect values in the Wildland Urban Interface (WUI) with the limited amount of resources available. Therefore, a new wildfire risk strategy and response tactic might prevent the likelihood of future catastrophic wildfires by managing an increasing wildfire load proactively.

Wildfire Management Problem Statement

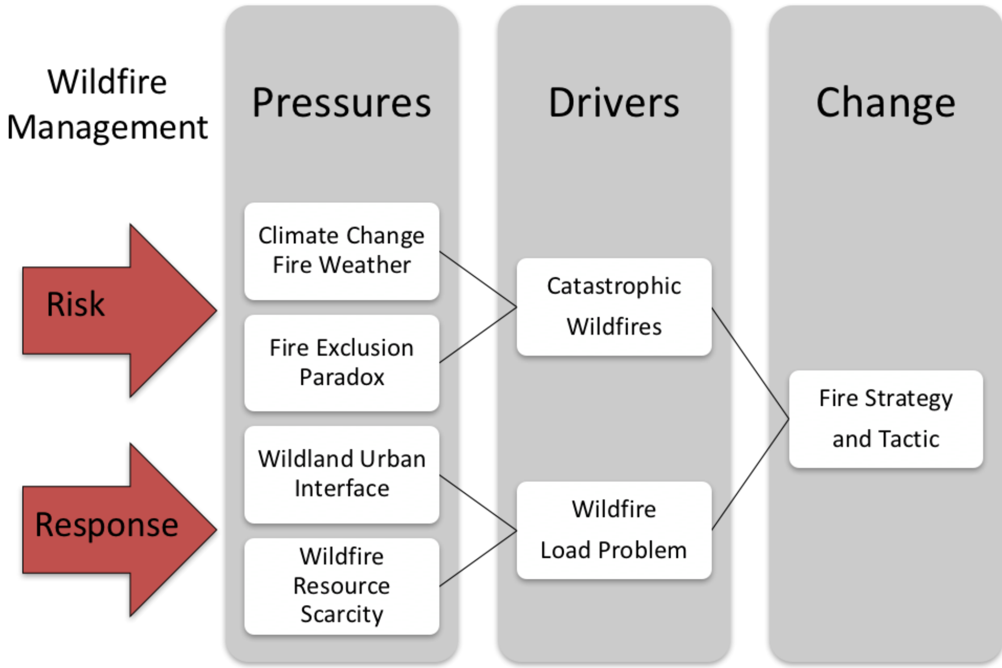


Figure 1. Management pressures that contribute to catastrophic wildfires and a wildfire load problem, which could change risk strategies and response tactics.

Climate Change Fire Weather

Climate change has an amplifying effect on fire activity (Flannigan *et al.* 2008), and as more frequently warm and dry conditions occur the probability of dry lighting (WMB 2010) and ignition increases (Flannigan *et al.* 2009). An early warning sign of climate change's effects on North America is the increased area burned in wildfires, which is associated with warmer temperatures caused by increasing CO_2 levels (Flannigan *et al.* 2005). Since drier fuels burn more readily (Van Wagner 1987), wildfires thereby burn with more intensity and grow larger (Westerling *et al.* 2006) and this makes them difficult to manage as a result of their resistance to control efforts (Wotton and Stocks 2006). This dynamic extends the wildfire season (Westerling *et al.* 2006), and is consequently exhausting available fire resources (Wotton and Flannigan 1993). Therefore, a greater wildfire suppression effort is required to combat the effects of climate change on wildfire activity in North America.

Wildfire management usually allows intense wildfires to grow larger, and focus their efforts on achievable objectives. Intense wildfires also pose greater risk to first responders because fire behaviour can quickly change and potentially overwhelm wildfire management's response capacity. Table 1 links fuel hazards with expected fire behaviour to determine a wildfire control tactic. These volatile conditions created by wildfires often pose significant threats to both first responders and the surrounding communities. When direct suppression tactics are too dangerous, fire managers consider indirect attack options (Alexander and Cole 1995), which often involve using natural and artificial boundaries to influence or inhibit wildfire spread. In this role, sprinkler systems could create a containment line to limit wildfire growth, and this would remove staff from dangerous situations while improving their effectiveness by allowing them to select easier areas to defend. Ultimately, reacting to wildfires is becoming an increasingly ineffective risk strategy; instead, wildfire agencies should focus on wildfire prevention using indirect tactics to manage a more volatile fire regime.

Table 1. Fuel moisture content relationship with fuel moisture codes to predict associated fire behaviour and anticipate wildfire control tactic (compiled from Alexander and Cole 1995, NRC 2016, Taylor *et al.* 1996)

Fuel Hazard and Fire Behaviour Tactics

Fire Danger	Fuel Moisture Codes FFMC	DMC	DC	Fire Intensity (kW/m)	C2 Rate of Spread (m/min.)	Fire Behaviour Description	Wildfire Control Tactic
Low	< 75	< 20	< 80	10 - 500	0.1 - 3	Creeping Fire	Self-extinguishment
Moderate	75 - 84	20 - 27	80 - 190	500 - 2,000	0.6 - 3	Surface Fire	Direct Attack
High	85 - 88	28 - 40	191 - 300	2,000 - 4,000	2 - 7	Torching Trees	Heavy Equipment
Very High	89 - 91	41 - 60	301 - 425	4,000 - 10,000	3 - 16	Crown Fire	Airtankers
Extreme	> 91	> 60	> 426	> 10,000	> 8	Spot Fires	Indirect Atrtack

Fire Exclusion Paradox

The exclusion of wildland fire might do more harm than good (Cohen 2008). In 1910, North America experienced devastating wildfires, leading to the development of a wildfire suppression strategy (Pyne 2008). Initial attack programs aggressively extinguished small wildfires before they grew beyond control, and this strategy continued with more wildfires suppressed in further remote areas with parachute, rappel, and helicopter wildfire crews (PBS 2002). After World War II (1939-1945) wildfire management agencies added aerial suppression to drop water and fire retardant on crown fires. As more development occurred in forested areas, society's fire risk tolerance diminished, and wildfire suppression programs became very effective at controlling low to very high-intensity wildfires. Fire exclusion policies perceived wildfires as harmful; this resulted in an aggressive suppression strategy, which can cause future dangerous wildfires (Filmon 2004).

Wildfire management must be prepared to take short-term calculated risks in order to sustain long-term ecological protection. Wildland fire disturbance is an important ecological process that maintains resilience through forest renewal. Prohibiting wildfires can alter the fuel complex from a healthy vigorous forest, to a stagnant forest in various stages of decline. Unhealthy forests are more susceptible to pest and disease outbreaks, which are often a precursor to wildfires. A responsible fire strategy acknowledges that wildfires will occur around communities, but preferably under controlled conditions, and burn programs can reintroduce wildfire back onto landscapes in a safe manner (Weber and Taylor 1992). Prescribed burn programs inherently reduce wildfire risk by fostering resilient ecosystems, and reconciling wildfire incidence with landscape objectives, this landscape management strategy recognizes humans as stewards of nature.

Catastrophic Wildfires

Dangerous fire weather and abundant fuels contribute to catastrophic wildfires (ABC 2014), and catastrophic wildfires are increasingly causing death, damage, and distress. Recent examples of disastrous wildfires include Firestorm 2003 (Filmon 2004), Black Saturday (State of Victoria 2010), the Flat Top Complex (ESRD 2012), and Horse River (Fort McMurray) wildfire of 2016. These wildfires had catastrophic consequences because they put people and their property in imminent danger. A wildfire strategy to reduce these risks is the development of prevention programs to help communities prepare for wildfires and mitigate their impacts. Sprinkler protection can serve as one facet of these strategies, as it works to reduce wildfire risk by allowing them to burn around endangered values. This not only reconciles their ecological benefits, but also decreases the likelihood of future high intensity wildfires by removing fuels.

Wildfire Resource Scarcity

The increased incidence of wildfires in North America is resulting in wildfire resource scarcity. Currently, resource exchange agreements supplement wildfire response capacity when demands exceed preparedness levels. Figure 2 illustrates the increasing mobilization of wildfire resources in Canada, and this trend is concerning because financial budgets are constrained and resources are costly. When resource requests are widespread, wildfire agencies, manage their own needs first; if there are no wildfire resources available (Taylor *et al.* 2006), actions are prioritized to minimize death and destruction. If a shift from direct to indirect wildfire response tactics occurred, it will improve utilization of the available resources while promoting long-term health of the ecosystems involved.

Canadian Interagency Forest Fire Centre (CIFFC) Resource Exchanges

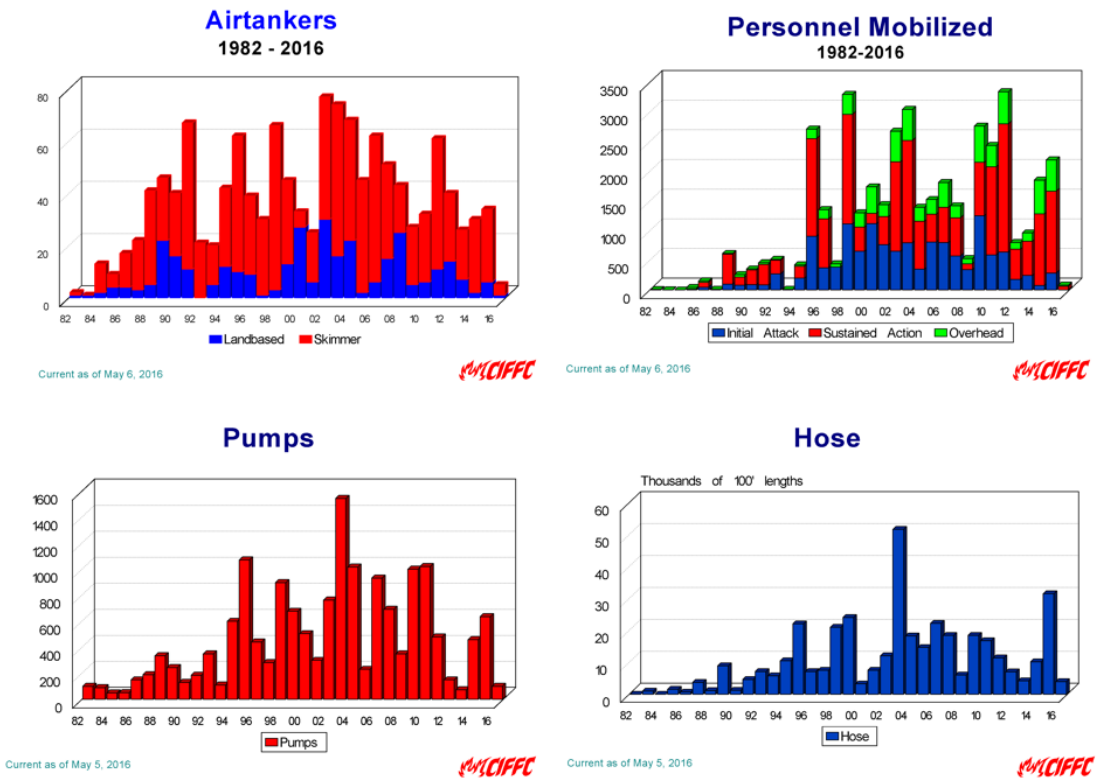


Figure 2. The mobilization of airtankers, personnel, pumps and hose between wildfire agencies from 1982 to 2016 in Canada (CIFFC 2016).

Modern wildfire suppression capacity is quickly becoming insufficient to meet the future fire load. For example, a doubling of wildfire resources would be required by 2040 for the province of Ontario to experience the same wildfire preparedness levels as 2006 (Wotton and Stocks 2006), and it is simply not feasible or realistic to increase resources, when that might not necessarily resolve the underlying causes. However, if wildfire management agencies maintain the current status quo, they will continue to be deficient in suppression resources and Ontario itself can expect a rate of approximately 25% escaped wildfires by 2040 (Wotton and Stocks 2006). Therefore, wildfire agencies should consider a change from direct to indirect tactics to prepare for more wildfires.

Wildland Urban Interface

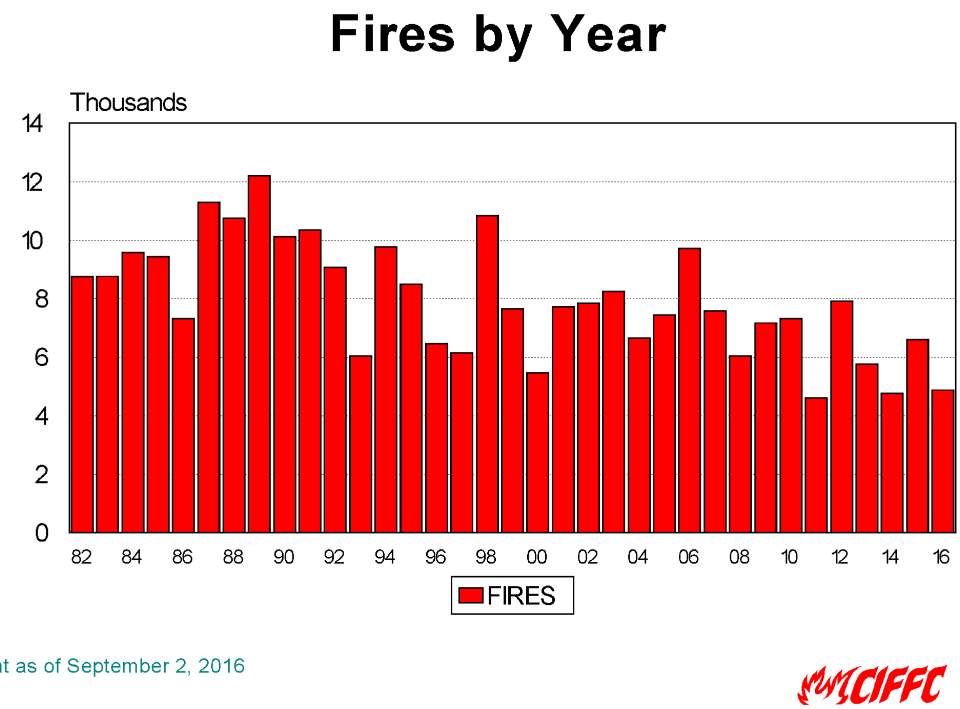
Managing wildfires in public and private spaces is often a contentious and difficult task. Urban sprawl into wildland fire environments represents an increasing probability for WUI conflict (McFarlane 2006, Peter *et al.* 2006), and many development decisions have been made with little thought about wildfire risk. This often results in difficult decisions about which values to protect – the interests of the private property owner or the general public management perspective. Usually critical infrastructure such as hospitals, power stations, and water facilities (EMBC 2000) are protected, then private property through structural triage (Partners in Protection 2003). To manage the fire load more effectively, citizens must take responsibility for their property when wildfire occur.

A shift towards public outreach could be very effective in reducing both the incidence and damage caused by wildfires. WUI wildfires are expensive to defend because many residents do not take the proper steps to protect their homes; however, fire prevention programs such as FireSmart (Partners in Protection 2003) and FireWise (AWFCG 2010, Bothwell 2006) can help to educate people on how to protect their property. For example, radiant heat and spot fires often cause structure fires, but engineering solutions during the development phase improves a structure's survival rating (Partners in Protection 2003). Using fireproof materials during construction increases a building's resistance to radiant heat (Walkinshaw and Ault 2009a), and the architectural design of a structure can itself be engineered to deflect embers by reducing catchment areas using obtuse corners and by covering open spaces (Quarles *et al.* 2010). These practices should be encouraged through building codes and fire insurance incentives (McGee *et al.* 2005, Headwaters Economics 2014) because property owners need to understand the implications wildfires can have on their property. By teaching people how to protect their property, wildland fire agencies will be able to focus on landscape management responsibilities.

Wildfire Load Problem

A cold front moving into a high-pressure ridge can cause thunderstorms and ignite numerous wildfires naturally (AFS 1983), and this requires fire managers to prioritize resources amongst the fire load over a short period. These situations can quickly exceed wildfire management capacity and often require assistance from allied agencies to manage priority wildfires. When analyzing the incidence of wildfires, it is important to distinguish between naturally caused wildfires and those resulting from the actions of humans. Wildfire prevention techniques as outlined above can help to reduce human-caused ignitions, which will in turn allow for increased allocation of resources to naturally caused wildfires. In fact, success achieved in wildfire prevention programs could correspond to the decline in human-caused wildfires. As illustrated in Figure 3, the total overall area burned continues to grow, meaning fire resource scarcity will continue to exist until tactics change.

Perhaps more importantly, approximately 3% of wildfires account for 97% of the area burned in Canada (Wotton and Stocks 2006). Some wildfires escape initial attack and expand to become “project” wildfires due to the fire response complexity. These wildfires often require an Incident Management Team (IMT) to mitigate potential threats to people and property, and as a result, they can strain wildfire management capacity by consuming large amounts of fire resources for extended periods. To better address the increasing area burned and manage large wildfires more effectively, indirect attack tactics could address project fires. This will not only help to alleviate resource constraints, but also reduce the risk of harm to wildfire personnel and the people and animals they work to protect. Sprinklers supported by prescribed burning can represent one of the keys tools needed to achieve this tactic, and are therefore useful to managing an increasing fire load.



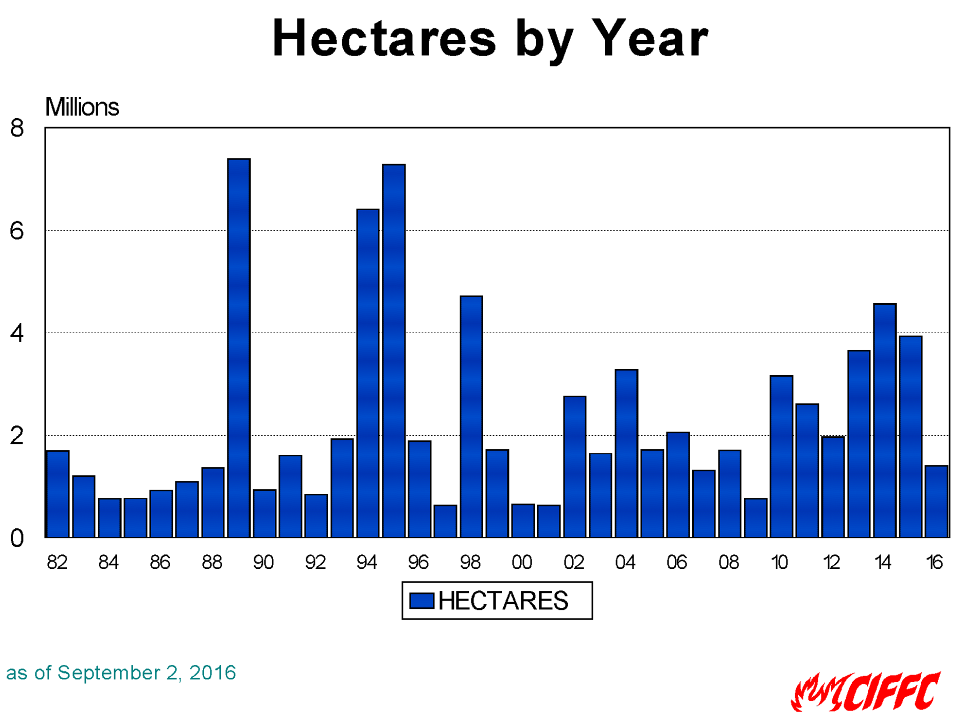


Figure 3. Number of wildfires and their area burned in hectares from 1982 to 2016 in Canada (CIFFC 2016).

1.2 Fuel Moisture

Weather conditions affect fuel moisture levels, which play an important role in understanding wildfire behaviour. However, fuel moisture research has largely focused upon the relative dryness of fuels' and their associated effect on wildfire behaviour. This study examines the effectiveness of sprinkler systems as a potential resource to reduce fire danger. Sprinkler-watering can infuse moisture into the atmosphere, dead soils, and living plants to reduce their probability of ignition, which enables wildfire agencies to decrease fuel hazard.

Fuel Hazard

The Canadian Forest Fire Danger Rating System (CFFDRS) predicts wildfire risk using fuel, weather, topography and ignition potential as its key determinants (Stocks *et al.* 1989, AFSC 2014). The Fire Weather Index System represents the foundation of CFFDRS and it tracks the drying and wetting of fuels in order to better anticipate their flammability and potential to spread (CFS 1984). Table 2 illustrates how wind speed, temperature, relative humidity, and rain are used to calculate fuel moisture codes and fire behaviour (Van Wagner 1987).

Table 2. Weather inputs and fuel moisture codes used to calculate fire behaviour indices (Van Wagner 1987)

Canadian Forest Fire Weather Index System Indices

Fuel Moisture	**Weather Input * includes month**				**FWI**	
Code	**Temp.**	**Rain**	**RH**	**Wind**	**ISI**	**BUI**
FFMC	x	x	x	x	wind	
DMC *	x	x	x			2/3
DC *	x	x				1/3

Fuel moisture codes are organized by soil layers and fuel size. More specifically, Fine Fuel Moisture Code (FFMC) refers to the relative dryness of the litter layer and fine fuels; Duff Moisture Code (DMC) represents loosely compacted duff and downed woody debris; and, Drought Code (DC) tracks seasonal trend of deep compacted soils and coarse woody debris (Van Wagner 1987). Greater FFMC, DMC, and/or DC values indicate a more susceptible fuel hazard, which in turn strongly influences ignition probability and the anticipated fire behaviour.

Fuel moisture affects fire behaviour based on the time required to preheat fuels, resulting availability of fuels for combustion, and residence time during combustion (Nelson 2001). Fire behaviour indexes use wind speed and fuel moisture codes to forecast wildfire growth and intensity for a given fuel type in a specific fire environment. The Fire Weather Index (FWI) estimates fire intensity, which is a good proxy for fire danger overall; Build-up Index (BUI) represents the amount of fuel available to burn, typically driven by DMC, although DC does contribute to seasonal trends; and Initial Spread Index (ISI) combines FFMC and wind speed to predict the fire rate of spread (Van Wagner 1987). If sprinkler-watering raises fuel moisture in targeted areas, it could minimize the fuel hazard and its associated fire behaviour to reduce the overall fire danger around values.

Alaska's fire season can create volatile fuel hazard due to its long daylight hours and resulting minimal moisture recovery achieved in fuels during evening hours (Beck and Armitage 2004). A study conducted by Jandt *et al.* (2005) in interior Alaska compared fuel moisture content measurements with the Fire Weather Index System to verify fuel hazard, and the results noted inconsistencies between field measurements and CFFDRS predictions. Specifically, CFFDRS was under-predicting feather moss drying rates in the spring and over-predicting them during the late summer. Therefore, it is crucial to ground-truth fuel moisture codes to understand the fuel hazard to calibrate CFFDRS's assumptions when formulating fire predictions. This research selected 6 research sites within interior Alaska to study fuel moisture changes.

Weather and Fuel Moisture

Weather is the most dynamic factor that influences fire environments (Countryman 1972). Warmer temperatures positively affect atmospheric moisture holding capacity, forming an inverse relationship with relative humidity readings (Countryman 1971). For example, black spruce (*Picea mariana*) and white spruce (*Picea glauca*) flammability is highly sensitive to short-term changes in relative humidity, and their fine fuels often burn during flaming combustion (Norum & Miller 1984). The atmosphere and dead fuels exchange moisture content in an attempt to reach equilibrium moisture content, generally, moisture adsorption occurs in dead fuels if the relative humidity is greater than 35%. When atmospheric conditions are hot and dry, sprinkler systems could soak fuels around values to lower the fire danger and its associated fire behaviour.

A precipitation event is a function of its duration and intensity (Bradshaw *et al.* 1984); more frequent precipitation measurements would provide greater resolution to rainfall duration and intensity. Forests absorb a fraction of the available water during rainfall, rainfall is not included in the Fire Weather Index System unless it is greater than 0.5 mm, 1.4 mm, and 2.8 mm of water for the FFMC, DMC and DC respectively. If duff is already wet, then less water will be retained during rainfall (Van Wagner 1987), as excess water will either become runoff or seep deeper into the duff (Johnson *et al*. 2012). Stocks (1970) observed greater rainfall caused more water retention, but with less water use efficiency. In Alaska, Miller (2013) found that duff reacts almost instantaneously to rain events at 6 cm depth, while at 13 cm there was a few hours' delay. This research seeks to quantify moss and upper-duff water absorption and retention after a sprinkler-watering treatment.

Ignition Probability

Daily weather trends affect dead organic fuel moisture (Countryman 1971, Bradshaw *et al.* 1984), although fuel size, arrangement, and bulk density also influence moisture exchange (Nelson 2001). Fine fuels dry faster than larger fuels because of their greater surface to volume ratio (Van Wagtendonk 2006). Similarly, woody debris decomposes slower than fine fuels, which compress into higher bulk densities that can hold more water (Benscoter *et al.* 2011). Bulk density is a good indicator of fuel arrangement, and indicates fuel connectivity, porosity and compaction, which affect drying and combustions rates. For example, Frandsen (1997) found feather moss density is 42.7 kg/m^3 with a 23% coefficient of variation from 0 to 25 cm soil depth. Deeper soils dry more gradually, except at the duff-mineral interface, where the mixing of soils can invert the trend (Stocks 1970). As soil layers approach a dried state they begin to plateau in moisture content (Stocks 1970), this process takes approximately 16 hours, 15 days, or 53 days for FFMC, DMC, or DC on a standard drying day in July (Lawson *et al.* 1997a). This thesis has measurements of feather moss and upper-duff species composition and bulk density in order to monitor the effects on sprinkler-watering moisture changes.

When assessing wildfire ignition probability, fuel can represent either a heat sink or source depending upon its moisture and inorganic content levels and bulk density (Lawson *et al.* 1997b). Wildfires usually start in dead fuels because they are drier; fuel is receptive to ignition when the moisture content is below approximately 28% (FFMC = 75) in fine fuels and 120% (DMC = 45) in upper-duff soils and woody debris (Wotton 2014b, Lawson *et al.* 1997b). Human-caused wildfires usually occur at the surface in fine fuels, whereas wildfires caused by lightning are generally in woody debris or upper-duff soils (Wotton 2014a). Mineral soil does not burn, but it can affect fuel moisture and combustion rates alternatively through its drainage and heat sink properties (Frandsen 1987), Frandsen (1997) found average inorganic content of feather moss is 18% with a

30% coefficient of variation. This research suggests that applying a sprinkler-watering treatment can prevent ignition of fuels around values at risk.

1.3 Sprinkler Protection

A few anecdotal accounts and studies elaborate on how sprinkler systems are a valuable tool for managing fire behaviour (State of Minnesota 2008). However, planning the deployment of large-scale sprinkler systems requires a plan for both the feasibility and functionality of using sprinklers to contain and prevent wildfires. Sprinkler tactics could evolve from their current use in structure protection and expand into wildfire operations.

Sprinkler Success Stories

My first exposure to sprinklers as a fire prevention and suppression tool occurred during a fire incident in 2012 in Fort Nelson, British Columbia. Many trees had collapsed into this fire making it difficult and dangerous to extinguish, and it occurred during the fall when resources are limited due to expiring personnel contracts. I decided to implement a partial fire suppression strategy to reduce the workload required to extinguish the wildfire, part of this strategy was to establish a sprinkler perimeter reinforced by a fuel-free zone created around the fire’s edge. Then ignition operations that burned smaller sized fuels to prevent fire escape. After burning, the sprinkler were moved to the burned area to water overnight, this enhanced fuel moisture providing greater opportunity for self-extinguishment. The suppression tactics used to combat this wildfire highlight sprinkler system effectiveness in fire management operations. It demonstrated how a partial suppression strategy supported by sprinkler systems and ignition operations could maintain the ecological benefits of wildland fire while simultaneously reducing the suppression efforts and resources required.

There are many other undocumented examples in which sprinkler protection has proven to be an effective defense against wildfires. A video shown in a Canadian Broadcasting Corporation (2015) article displays how a sprinkler protection setup around a lakeside cabin was able to stop a stand-replacing crown fire in Saskatchewan. When the Ham Lake and Gunflint Trail wildfires spread into communities protected by sprinklers, Johnson *et al.* (2008) documented that sprinklers protected surrounding vegetation irrespective of fire behaviour. Moreover, sprinkler systems installed to protect infrastructure had a 98% success rate in protecting structures when working; however, 89% of structures burned when sprinklers failed *(*Johnson *et al.* 2008*)*. It is therefore clear that existing sprinklers should be rigorously tested and well maintained to avoid malfunctions (Rain Bird 2010a). It may not be possible to water the entire forest, but sprinklers can water fuels around values to prevent wildfires.

Sprinkler Tactics

Sprinkler systems represent a preventative action for defending against wildfires, and are becoming an increasingly common tool for defending values as described below. Depending upon the operational objective, different sprinkler systems can be setup. For example, a line sprinkler system creates a firebreak for ignition operations that can contain wildfires indirectly; this would allow responding agencies to determine advantageous areas to control the wildfire at desirable times of day. When using a line sprinkler system (Figure 4), water pressure diminishes sequentially for each additional sprinkler; however, a water pressure regulator or adjustable valves can regulate water flow to each sprinkler. A loop sprinkler system (Figure 4) uses a three-way valve to encircle an area to protect a value, and this setup can equalize water pressure amongst sprinklers, increasing efficiency up to 20% (OMNR 2003). When using hybrid sprinkler system that combines line and loop sprinkler systems, sprinkler systems are setup according to water pump volume and hose diameter size to conserve water and gas supplies.

Sprinkler System Configurations

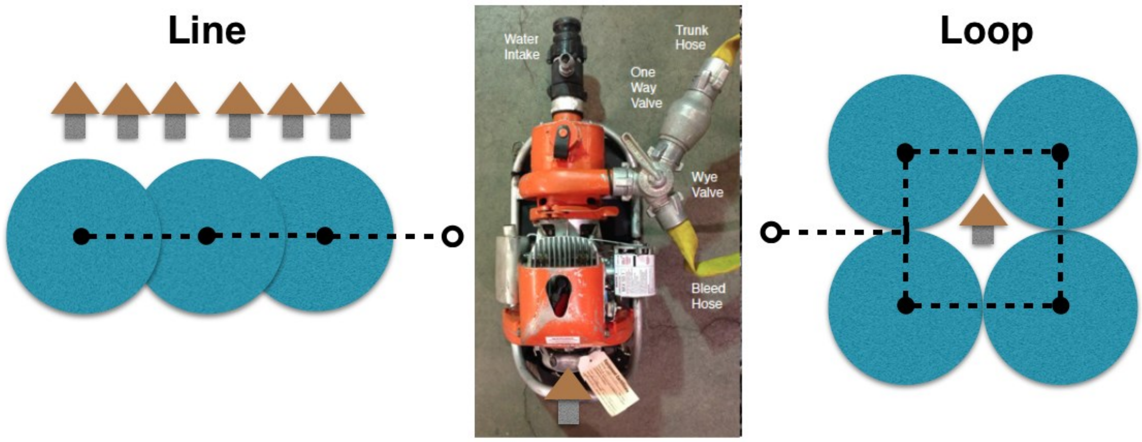


Figure 4. Line and loop sprinkler system configurations.

A sprinkler deployment plan describes an operational objective including sprinkler system setup and activation procedures. Decision points for sprinkler operations and backfiring opportunities are marked on a map to provide guidance for actions. Once a sprinkler containment line has begun watering, ignition operations can widen the firebreak beyond spot fires distance from the approaching wildfire (Fogarty 1996). When protecting multiple structures in close proximity, a sprinkler perimeter could stop the advancing wildfire, and depending upon the wildfire’s approach, further defensive units are setup for activation. This would represent a hybrid sprinkler system as the line sprinkler system creates a perimeter whereas loop sprinkler systems are for specified defensive units. In this system, the sprinkler perimeter would use larger diameter hoses for a line sprinkler system and at least two water pumps, and then smaller diameter hoses would attach defensive units to protect critical areas using a loop sprinkler system. If wildfire management becomes more familiar with sprinkler tactics, both their use and capabilities will grow. Sprinkler deployment could become a valuable tool in achieving operational objectives to support wildfire suppression indirect tactics.

Sprinkler Systems

Sprinklers are often setup during wildfires alerts and evacuations; this requires time for placement whereas a proactive installation eliminates deployment delay. A sprinkler site should have an independent water source because public water systems can fail during wildfires. For example, when trees or power poles burn, they disable electrical infrastructure, which can in turn affect local water pumping systems. An emergency supply of water could be a cistern, which can be underground if there is no available water source. Water hoses must also be protected from burning as any damage caused could release water pressure and deactivate the sprinkler system overall (Walkinshaw and Ault 2009b). In the event of wildfire, it is paramount that first responders have safe access to the water pump in order to pressurize sprinklers during evacuations, furthermore, leaving access points at critical areas for a hose and nozzle helps firefighters to extinguish any spot fires that develop upon return.

When planning a sprinkler system, it is important to map hose distance, elevation changes, and sprinkler placement in order to calculate projected water pressure along the specified lines. More specifically, extended hose distances will cause pressure loss from friction inside the hose, and elevation changes may require additional water pumps or water devices that neutralize water pressure to prevent hoses from bursting. Conversely, a gravity-driven water system pressurizes sprinklers placed below the water source, and this often works well as many communities are located on the natural decline created by floodplains. An efficient sprinkler system conserves water while maximizing water pressure.

Once a sprinkler setup has been planned, sprinkler-watering treatment for a given intensity and duration can be calculated. This experiment sought to control sprinkler-watering intensity using a 345 kilopascals water pressure regulator, isolating sprinkler-watering duration effect. Sprinkler-watering intensity refers to the amount of water that flows from a sprinkler nozzle, and nozzle size and water pressure do affect a sprinkler’s throw radius and water flow (Quintilio *et al.* 1971, Rain Bird 2010b). The sprinkler analyzed in this was a Rain Bird brass deluxe impact sprinkler on a hose-end spike base that sprays 12.2 m radius and delivers 18.9 L per minute at 345 kilopascals water pressure (Rain Bird 2010c). This research tests sprinkler-watering duration levels to monitor watering distribution and changes in fuel moisture content at 6 lowland boreal forest sites.

1.4 Thesis Rationale

There is already considerable evidence that sprinklers are effective at preventing wildfires, quantitative research concerning their efficacy is relatively limited. People often speculate that a sprinkler spray creates a microclimate that suppresses falling embers in order to reduce spot fires. However, Ault (2009) monitored relative humidity changes surrounding a sprinkler in an open field, stating that wind dispersed the humid air rather than lingering around. That study led to my research interest on water distribution and fuel moisture changes caused by a sprinkler-watering treatment. Protection from sprinklers wetting fuels' surface is obvious, however, water absorption and retention in the analysis of this process is less apparent. This experiment examines sprinkler systems role in modifying fuel moisture for hazard reduction programs.

Research Questions

Fuel moisture changes from a sprinkler-watering treatment needs to be measured in order to establish a desired fuel hazard reduction. Sprinkler operations could occasionally water fuels during dangerous fire periods to reduce their hazard values. To prevent ignition, Johnson *et al*. (2008) recommend further research into the amount of sprinkler-watering treatment needed over a 24-hour period to prevent ignition, and this study seeks to address this question. Specifically, this study aims to answer the following two research questions:

1. In lowland boreal forests around interior Alaska, what is the water distribution of a Rain Bird (2014a) brass deluxe impact sprinkler on a hose-end spike, receiving 345 kilopascals of water pressure?

2. What is the recommended sprinkler-watering treatment to change moisture content in red-stemmed (*P*leurozium schreberi) and stair-step (*Hylocomium splendens*) feather mosses at 0-5 and 5-13 cm depths?

Establishing this information will help to quantify sprinkler-watering treatment's efficacy, and thereby allow fire managers to plan sprinkler protection operations.

Hypothesis

Sprinklers are only effective if they are able to distribute water throughout lowland boreal forests. It is likely that vegetation could block a sprinkler's spray to limit its radius. In this capacity, sample distance from each sprinkler is a covariate to determine water distribution for each plot. The hypothesized treatment effect for sprinkler-watering duration in Figure 5 shows that moss moisture changes will increase pass the ignition probability threshold until sprinkler-watering is complete, and then it will slowly dry as time passes.

Sprinkler-watering Treatment Hypothesis

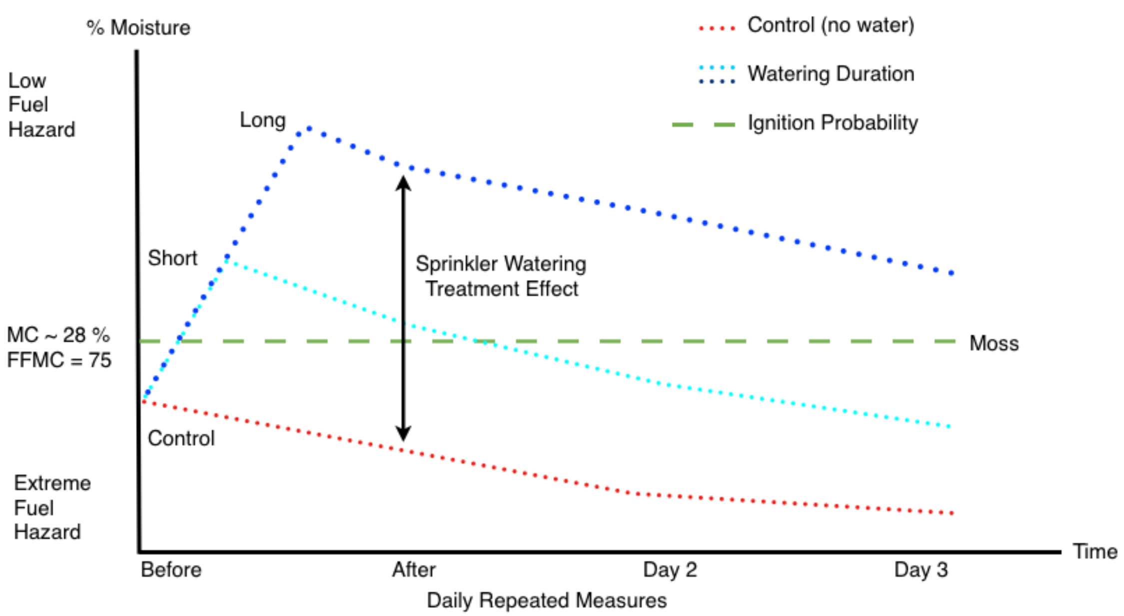


Figure 5. Hypothesized fuel hazard changes caused from sprinkler-watering.

The hypotheses of this thesis are below:

- A longer sprinkler-watering duration will cause a greater change in fuel moisture content until it reaches a point of saturation.
- Feather moss species might affect fuel moisture changes.
- Bulk density will positively influence fuel moisture holding capacity.

Research Aim

The research aim of this thesis is to restore, promote and maintain wildfire-dependent ecosystems by allowing fires to burn around values by protecting them with sprinklers positioned to stop wildfires. Sprinkler protection enhances resource utilization to reduce costs (Maffey 1983) as they are relatively inexpensive (Quintillio *et al.* 1971), and automation of sprinkler systems can optimize water use efficiency (Rain Bird 2014b). This research quantifies a sprinkler-watering treatment that increases fuel moisture content beyond ignition potential in moss and upper-duff soils. Helping fire managers to determine an appropriate sprinkler-watering duration to inhibit fire intensity or eliminate the probability of ignition.

This study suggests that sprinkler programs that incorporate both fuel management and ignition operations can manage wildfires effectively. Sprinkler systems can meet a variety of operational objectives beyond their traditional structure protection niche. An increase of sprinkler tactics could also lead to innovation in products and services to assist with wildfire prevention strategies. By improving their familiarity amongst wildfire management programs, new indirect attack sprinkler tactics could improve both the safety of first responder personnel and surrounding communities, while enhancing workforce productivity to alleviate resource scarcity pressures caused by an excessive wildfire load.

2 Methods and Data

This experiment was conducted in 8 lowland boreal forests sites around Fairbanks, Alaska. Each site contained 2 watering duration levels and a control treatment; each treatment had 4 plots that were measured 4 times before and after sprinkler-watering. Samples were taken throughout the afternoon to measure water distribution and how it caused moss and upper-duff moisture changes that were used to develop a sprinkler-watering curve. After sprinkler, testing, qualitative and quantitative covariates were collected to explain the environmental variation. A sampling protocol is documented for each repeated measure, including data collection for site and sample locations.

2.1 Methods

Lowland boreal forest sites were selected for this experiment because their feather moss and upper-duff soils are highly flammable when dry. This research's experimental design procedures are documented to allow for replication of this study at other sites. The sampling protocol describes site setup, and how the repeated measures and covariate data was collected. This data calculates tree stocking, bulk density, sprinkler equivalent rainfall, moisture changes, and FFMC and DMC to determine the sprinkler-watering treatment effect on fuel hazard.

Lowland Boreal Forests

Lowland boreal forests have flammable trees and deep organic soils (Chapin III *et al.* 2006), and their close proximity to water sources makes them an ideal candidate for sprinkler testing. It took approximately one week to setup the site, conduct field sampling, apply sprinkler-watering, measure the response and dry the samples collected before site demobilization. Table 3 lists each site's name, geographic coordinates, and experiment commencement date; whereas Figure 6 displays a satellite image of selected site locations within interior Alaska.

Sprinkler-watering testing should also occur when moss and upper-duff is dry enough for combustion and no rain is forecasted within the week.

Table 3. Sites number, name, coordinates and start dates for each experiment; Fort Wainwright sites were shaded in red because of sprinkler failure

Research Sites

Site	Name	Latitude	Longitude	2013
1	Fort Wainwright 1	64° 49.342'N	147° 34.203'W	June 2nd
2	Fort Wainwright 2	64° 49.296'N	147° 34.117'W	June 12th
3	Poker Creek	65° 9.116'N	147° 28.942'W	June 20th
4	Shaded Fuelbreak	64° 47.970'N	147° 20.589'W	June 28th
5	Adjacent Forest	64° 48.013'N	147° 20.605'W	July 5th
6	Blueberry Bog	64° 54.782'N	147° 50.093'W	July 16th
7	Jenny Creek	64° 52.652'N	146° 59.317'W	July 27th
8	Eielson	64° 35.430'N	147° 1.473'W	Aug 2nd

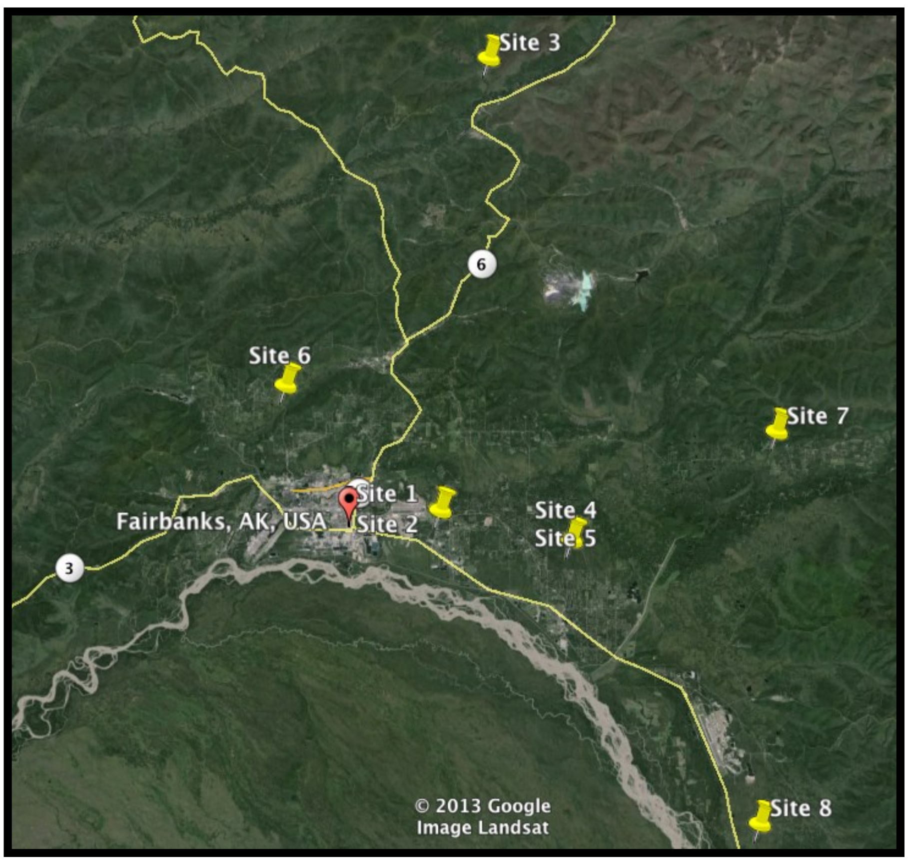


Figure 6. Lowland boreal forest sites near Fairbanks, Alaska that were sprinkler tested (Google 2013).

Feather moss was selected as an indicator species because it is sensitive to fuel moisture changes and acts like a sponge (Wilmore 1999). The two common feather moss species sampled in this research are shown in Figure 7: Stair-step (*Hylocomium splendens*) and red-stemmed (*Pleurozium schreberi*). As illustrated, stair-step feather moss's horizontal alignment is similar to miniature broadleaf trees, and red-stemmed feather moss stands vertically like conifer trees. This is important because fuel alignment has been shown to impact on flammability, as demonstrated by Wotton's (2009) cured grass moisture model; therefore, feather moss anatomical structure could affect fuel moisture dynamics.

Feather Moss Species

Stair-step *Hylocomium splendens* (Hedw.) Schimp.

Red-stemmed *Pleurozium schreberi* (Brid.) Mitt.

Figure 7. Stair-step and red-stemmed feather moss species that were sampled to measure moisture changes.

Feather moss is a surface fuel that decomposes and accumulates into ground fuels known as duff; these fuel layers (Figure 8) have different moisture properties. The litter (L) arrangement of live and dead moss has a higher surface to volume ratio and a lower bulk density than duff fuels. Duff fuels are distinguished by their stage of decomposition: Upper-duff has partially decomposed organic material with white fungal hyphae at fermentation (F) stage of decomposition, while lower duff has darker decomposed humus (H) soil with greater bulk density. Beneath these organic fuels were inorganic mineral soils that contain a mixture of sand, silt, and clay formed by local parent material.

Feather Moss Soil Profile

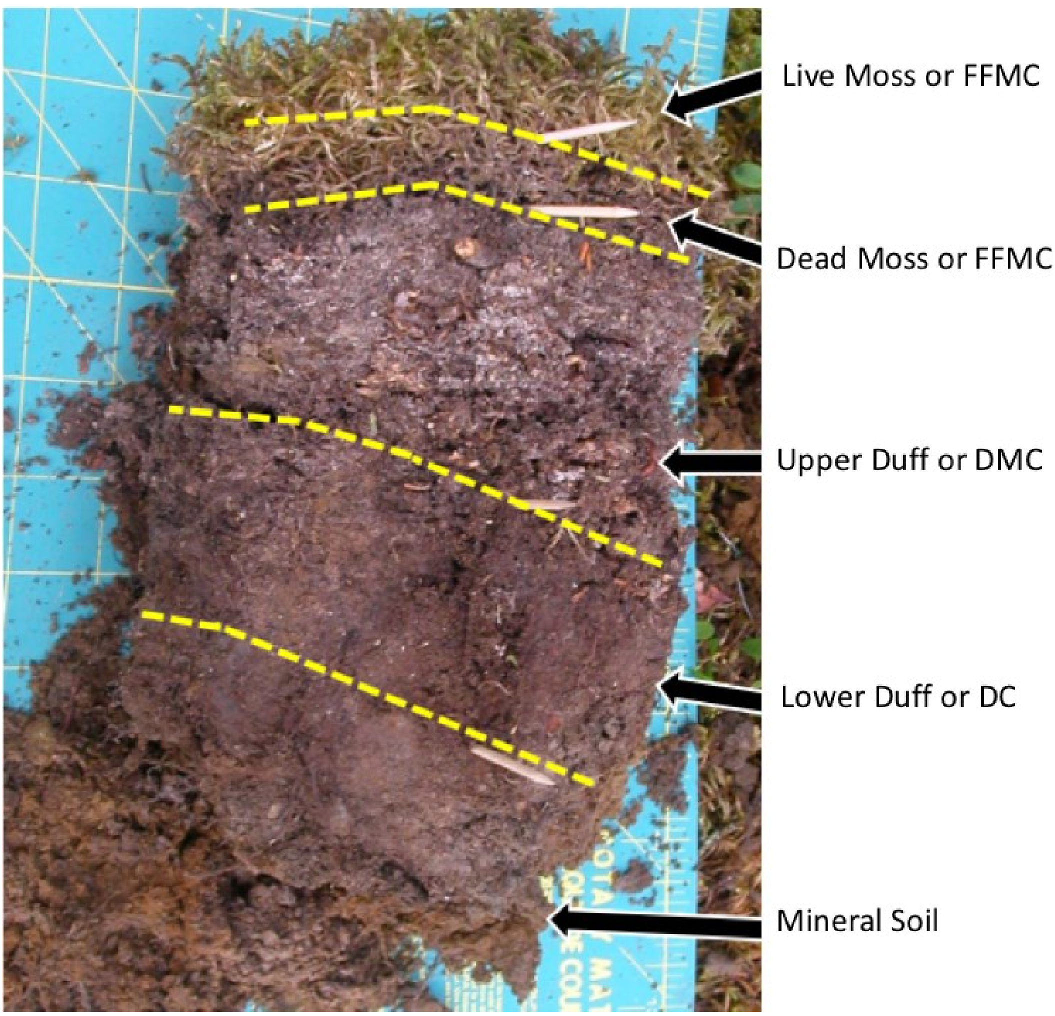


Figure 8. Feather moss profile has distinct layers for sampling (photo modified from (Barnes *et al.* 2012).

Experiment Design Procedures

A site diagram in Figure 9 illustrates the experimental design used for this research. Sprinkler-watering treatment levels were the amount of gas supplied to each water pump, and each site tested 2 sprinkler-watering treatment levels and 1 control treatment. A treatment had 4 plots that contained 4 time sets to produce 48 sample locations per replicate. Materials for this study are in Appendix A.1.

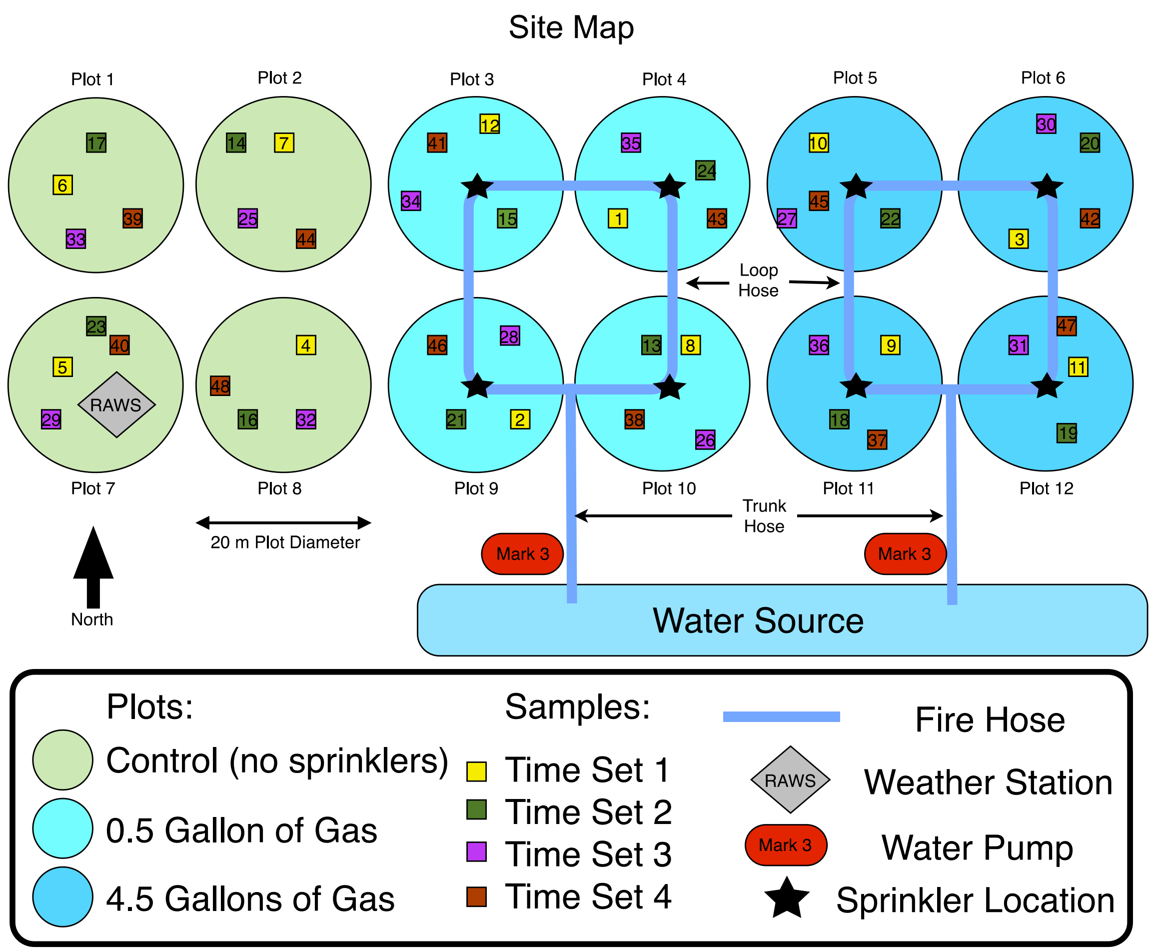


Figure 9. A site map showing 12 treatment plots containing 48 sample locations for 2 sprinkler-watering levels and a control treatment.

Independence of units was achieved through spatial and temporal randomization of sample locations within a plot. Sample positions were randomly selected by dropping 4 numbered markers (1 to 4) onto a plot map, and this process was repeated 12 times for each plot within a site. A plot was split into 4 time sets designed to monitor fuel moisture changes throughout the afternoon, the numbered markers (1 to 4) represent the time set of each sample within a plot. As shown in Table 4, plot-sampling order was determined by randomly drawing twelve numbers (1 to 12) representing plots for each of the 4 time sets.

Table 4. Daily plot sampling order for each sample location within a time set

Time Set	Site Sample Order											
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
1	Plot 4	Plot 9	Plot 6	Plot 8	Plot 7	Plot 1	Plot 2	Plot 10	Plot 11	Plot 5	Plot 12	Plot 3
2	Plot 10	Plot 2	Plot 3	Plot 8	Plot 1	Plot 11	Plot 12	Plot 6	Plot 9	Plot 5	Plot 7	Plot 4
3	Plot 2	Plot 10	Plot 5	Plot 9	Plot 7	Plot 6	Plot 12	Plot 8	Plot 1	Plot 3	Plot 4	Plot 11
4	Plot 11	Plot 10	Plot 1	Plot 7	Plot 3	Plot 6	Plot 4	Plot 2	Plot 5	Plot 9	Plot 12	Plot 8

Identical sprinkler system configurations were setup between watering treatments to determine the sprinkler-watering duration needed to modify fuel hazard levels to prevent ignition. As shown in Figure 10, the throttle was set to the fourth click on all water pumps to ensure consistent gas consumption. Loop sprinkler systems was installed to equalize water pressure within the hose, and a 345 kilopascals water pressure regulator was attached to the hose before the sprinkler, this was verified using a water pressure gauge. These sprinkler-watering controls were intended to isolate sprinkler-watering duration effect on water distribution and fuel moisture changes within a plot.

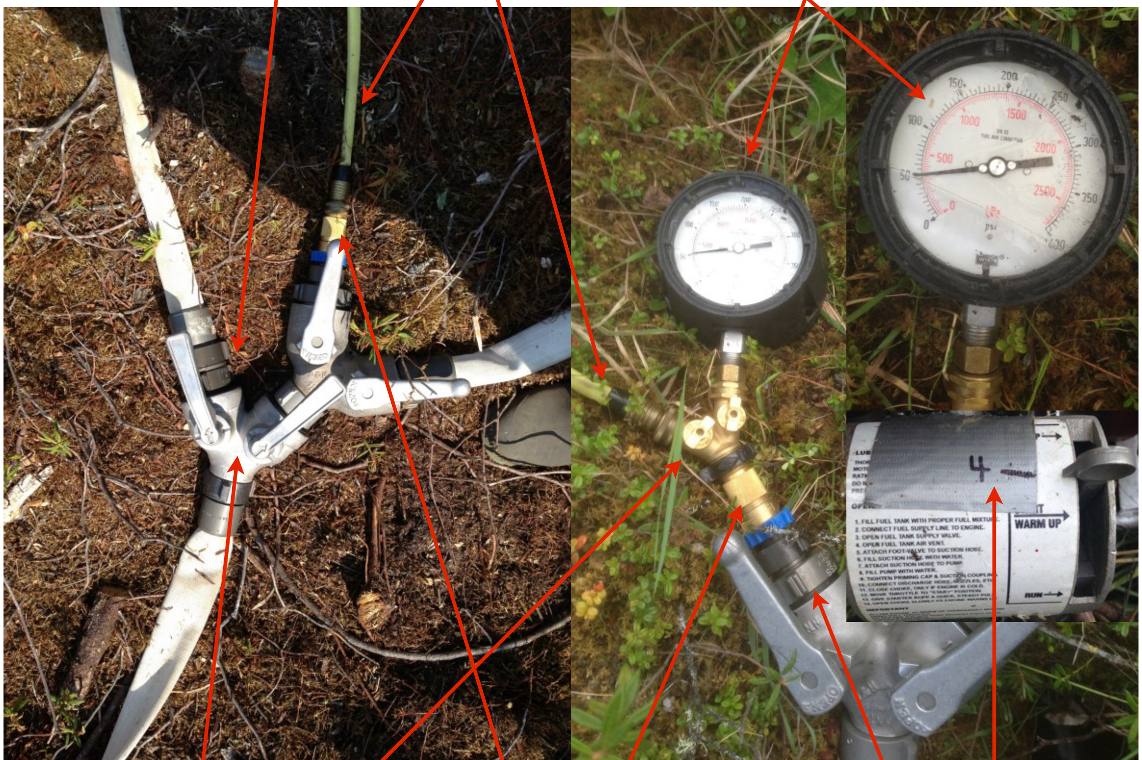


Figure 10. Water pump was set to throttle level 4 each sprinkler was connected with a 345 kilopascals water pressure regulator to control sprinkler-watering intensity.

This experiment examined 8 lowland boreal forests sites testing 7 sprinkler-watering duration levels and a control treatment (Table 5). The sprinkler-watering treatment levels were expressed as fixed amounts of gas because it was impractical to stay awake during the evening hours of operation. However, a sprinkler control experiment was performed to assess the amount of operation time for each sprinkler-watering treatment level applied. A brass deluxe impact sprinkler on tripod base was initially selected for the experiment due to its position above the shrub layer resulting in a longer spray distance. However, the tripod sprinkler malfunctioned at the Fort Wainwright sites, causing it to be replaced by a brass deluxe impact sprinkler on hose-end spike base (Rain Bird

2014a). Sprinkler systems were operated during the evening to maximize their water use efficiency.

Table 5. Watering duration levels expressed as gas and time; Fort Wainwright sites shaded in red were removed due to sprinkler failure.

Treatment Plots

Lowland Boreal Forests Sites	Control Treatment At Each Site		Sprinkler-watering Treatments Level 1 of 7		Sprinkler-watering Treatments Level 2 of 7	
	Gas (L)*	Time (Min.)**	Gas (L)*	Time (Min.)**	Gas (L)*	Time (Min.)**
Fort Wainwright 1	0	0	4.2	60	17.0	240
Fort Wainwright 2	0	0	4.2	60	17.0	240
Poker Creek	0	0	1.9	218	17.0	869
Shaded Fuelbreak	0	0	3.8	189	11.4	532
Adjacent Forest	0	0	3.8	206	11.4	532
Blueberry Bog	0	0	4.2	218	17.0	869
Jenny Creek	0	0	7.6	424	15.1	776
Eielson	0	0	1.9	98	7.6	424

* Gas consumed was derived from lowland boreal sprinkler-watering experiment.

** Watering time was derived from sprinkler-watering control experiment.

Water and organic containers (Figure 11) were sampled before and after sprinkler-watering treatment to measure equivalent rainfall and fuel moisture changes. The 96 water containers were covered by a 6 mm screen lid to prevent contamination from debris, while allowing sprinkler-watering to be collected. Since organic soils are rather variable, each site used 48 moss and 48 upper-duff containers to measure fuel moisture changes. The moss (0-5 cm) and upper-duff (5-13 cm) containers had a 6 mm screen attached to the bottom to withhold organic matter, but permit water flow through the sample. These sample containers were labelled to identify their tare weights and reused for each site.

Sample Containers

Figure 11. Water, moss, and upper-duff containers used for repeated measures.

Organic samples were cut from the forest floor using a knife, and then they separated into moss and upper-duff layers at 5 cm and 13 cm respectively using scissors. Separated organic layers were then placed into their respective container and back into the ground. The 2 water containers were aligned with the sprinkler spray and imbedded into the ground at approximately 15 cm from the organic containers as shown in Figure 12. A site setup datasheet found in Appendix A.2 records the sample treatment and container numbers installed for each sample location. A numbered flag was also positioned on the leeside of the sprinkler spray to assist with field navigation when following the sampling order.

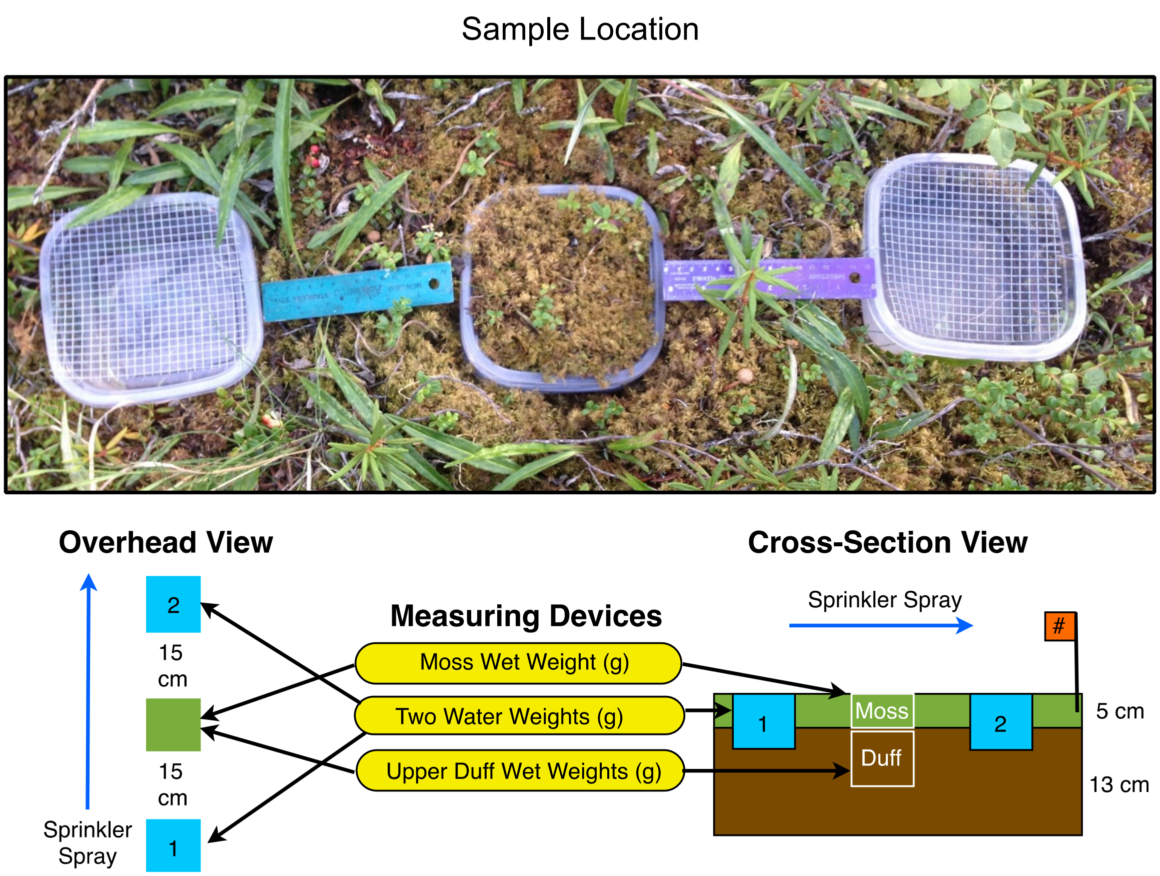


Figure 12. A sample location has 3 measuring devices arranged in the direction of the sprinkler spray.

2.2 Data

This section describes the sampling protocol and its data calculations.

Sampling Protocol

Sprinkler-watering distribution was determined by placing water containers alongside the organic samples; their mean water weight was then converted into equivalent rainfall. The changes in moss and upper-duff weights between repeated measures indicated fuel moisture absorption and retention. Figure 13 demonstrates how the organic and water containers were weighed in the field for each daily repeated measure. The mean of water captured was an independent factor and changes between fuel moisture content was the dependent variable.

Repeated Measure Sampling

Figure 13. Sampling moss, upper-duff and water containers in the field.

All sampling information was recorded on a datasheet, which can be found in Appendix A.2. Sampling protocol for repeated measures was as follows:

1. Find sample location flag markers using the site map (Figure 9).
2. At the sample location, place scale on hard and level surface.
3. Turn on scale, and press tare button to reset the scale.
4. Weigh moss container on the scale's center.
5. Record moss container weight on the sampling datasheet.
6. Weigh upper-duff container on the scale's center.
7. Record upper-duff container weight on the sampling datasheet.
8. Place the upper-duff container, then moss container back into the hole.
9. Weigh water containers individually on the scale's center.
10. Record both water containers' weight on the sampling datasheet.
11. Throw away water, and place water container back into original position.
12. Record time of sample on the sampling datasheet.

Be sure to include sampling dates, site and observer name for each experiment.

Organic samples were then transported to the lab for drying. Before removing samples from their location, an overhead photo was taken as visual record. In the lab, organic samples were dried for 24-hours at 100^{o}C in an oven to obtain their oven-dried weights (Lawson and Dalrymple 1996). Oven-dried moss and upper-duff weights were recorded on the sampling datasheet.

Covariate Data

Weather, site and sample covariates were documented to explain the environmental condition between sites and samples that could affect results:

Weather:

- Precipitation
- Solar radiation
- Wind speed
- Relative humidity
- Temperature

Site:

- Measurement Date
- Stand photo
- Tree Diameter
- Forest composition
- Tree stocking

Sample:

- Measurement time
- Location photo
- Location distance
- Moss species
- Canopy Closure

Local weather conditions can influence fuel moisture changes during the sprinkler-watering experiment (Lawson and Armitage 2008). For example, a warm and dry air mass will result in a quicker evapotranspiration rate than a cool and wet air mass. To monitor wind speed (km/hr.) and direction (degrees), precipitation (mm), relative humidity (%), temperature (^{o}C) and solar radiation (kW/m^2) a quick deploy Remote Automated Weather Station (RAWS) shown in Figure 14 was setup in a control treatment plot at each site. The wind anemometer measured a 2 m wind speed and wind direction was determined by orienting the RAWS cabinet north with a handheld compass. The air temperature and humidity sensors were encased in a solar radiation shield, while a pyranometer measured total light overhead. Precipitation events were avoided using weather forecasts; however, a rain-tipping bucket was also included to measure any rain. These weather observations were logged and transmitted to an online database using an antennae, solar power and battery (FTS 2014).

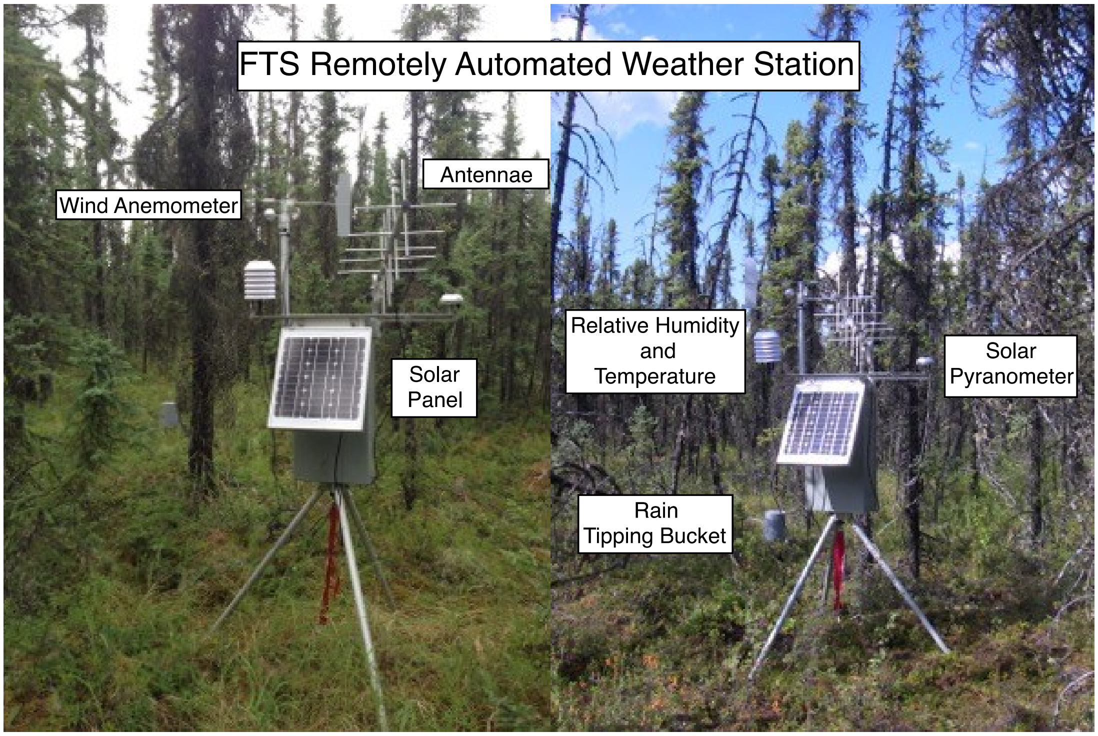


Figure 14. A portable weather station measuring weather in control plots.

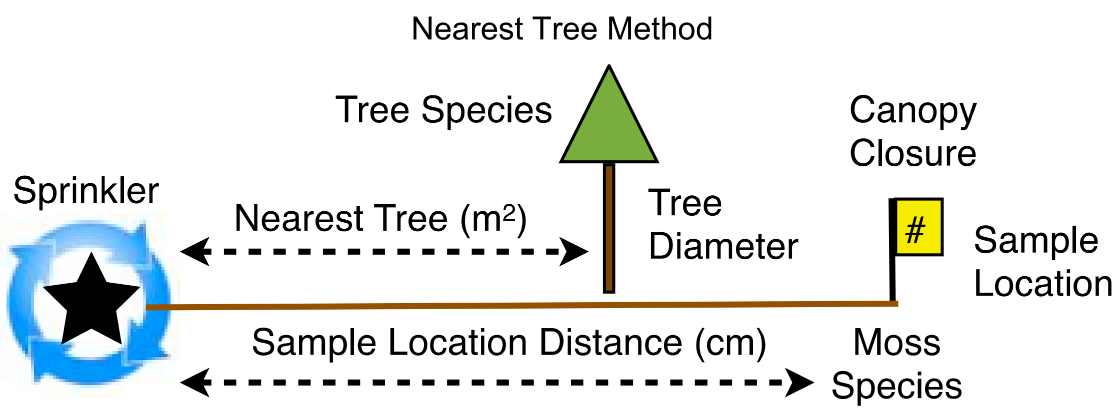


Figure 15. Nearest tree method covariate data collection for each sample.

Differences between lowland boreal forest sites and samples were documented using photos and the nearest tree method (Figure 15). Observations were recorded on the covariate datasheet found in Appendix A.2, on the next page is the nearest tree sampling protocol followed for each sample location:

1. Connect the sample location to the sprinkler using a measuring tape.
2. Record sample distance from sprinkler on the covariate datasheet.
3. Moved the center of a 1 m ruler along the measuring tape until the ruler reaches the nearest tree or sample location.
4. Record area travelled to the nearest tree on the covariate datasheet.
5. If a tree was reached, record the tree species on the covariate datasheet.
6. Measure tree diameter with a diameter tape at 1.3 m height.
7. Record tree diameter on the covariate datasheet.
8. Hold a spherical densiometer over the sample location to measure canopy closure by counting the dots covered by trees on the parabolic mirror.
9. Record the number of dots covered by trees on the covariate datasheet.
10. Feather moss species were categorized into red-stemmed feather moss, stair-step feather moss, or mixed feather moss on the covariate datasheet. For a feather moss species to be considered dominant, it must have greater than 70% abundance within the organic container. If there was a relatively even distribution of two moss species, then feather moss species was labeled as mixed.

This process was completed for all samples to document environmental variation.

Calculations

Tree stocking density for each site was calculated using the total distance travelled to nearest trees divided by number of trees counted (Equation 1); this measurement expresses the likelihood of a tree obstructing sprinkler spray. If no tree was observed between sprinkler and sample location, then the nearest tree distance becomes the sample distance and no tree is tallied for the sample.

Equation 1. Tree stocking per m^2 for the sample locations

$$\text{Stocking}\left(\frac{\text{m}^2}{\text{tree}}\right) = \frac{\Sigma\,(\text{Nearest Tree Distance})^2}{\Sigma\,\text{Tree Count}}$$

Bulk density was used as a measured compactness of fuel, which could influence water absorption and retention. First, container tare weight was subtracted from oven dried weights to get dried organic weight, and then dried organic weight was divided by container volume to calculate bulk density and multiply by 1,000 to convert into kilograms per metres cubed (Equation 2 and 3).

Equation 2. Moss containers bulk density for each sample container

$$\text{MossBulk}\left(\frac{\text{kg}}{\text{m}^3}\right) = \frac{\text{MossDry (g)} - \text{MossTare (g)}}{12\text{ cm} \times 12\text{cm} \times 5\text{cm}} \times 1{,}000$$

Equation 3. Upper-duff containers bulk density for each sample container

$$\text{DuffBulk}\left(\frac{\text{kg}}{\text{m}^3}\right) = \frac{\text{DuffDry (g)} - \text{DuffTare (g)}}{12\text{ cm} \times 12\text{ cm} \times 8\text{cm}} \times 1{,}000$$

To assess if sprinkler-watering duration affects fuel moisture changes, water containers capture precipitation that a plot receives during the experiment. Water container weight before treatment (t) was subtracted from water weight after treatment (t+1) to calculate sprinkler-watering applied in grams (Equation 4), then both water container weights were averaged to produce the sample's watering treatment (Equation 5). After calculating the sprinkler-watering treatment, water weight was converted into equivalent rainfall in millimetres by dividing 14.4 (Equation 6) because the water container's had a 12 cm by 12 cm surface area.

Equation 4. Change in water container weight between repeated measures

$$\Delta\text{ Water 1 (g)} = \text{Water } 1_{\text{t+1}}\text{ (g)} - \text{Water } 1_{\text{t}}\text{ (g)}$$

$$\Delta\text{ Water 2 (g)} = \text{Water } 2_{\text{t+1}}\text{ (g)} - \text{Water } 2_{\text{t}}\text{ (g)}$$

Equation 5. Average changed water weight for a particular sample location

$$\Delta\text{ Water (g)} = \frac{\Delta\text{ Water 1 (g)} + \Delta\text{ Water 2 (g)}}{2}$$

Equation 6. Conversion of averaged changed water weight to equivalent rainfall

$$\text{Rain (mm)} = \frac{\Delta \text{ Water (g)}}{14.4}$$

Moss and upper-duff sample wet-weight was subtracted by dried-weight to produce gravimetric moisture expressed as percentage of oven-dried weight (Equation 7). The difference between before (t) and after (t+1) gravimetric moisture content measures sprinkler-watering treatment effect (Equation 8). Moss and upper-duff gravimetric moisture content can be converted to FFMC and DMC fuel moisture codes (Equation 9 and 10) to express the change in fuel hazard caused from sprinkler-watering. These equations are important to this research because they account for fuel moisture changes, which were translated into fuel hazard reductions caused by the different sprinkler-watering durations.

Equation 7. Gravimetric fuel moisture content of moss and upper-duff layers

$$\text{Moss (\%)} = \frac{\text{MossWet (g)} - \text{MossDry (g)}}{\text{MossDry (g)} - \text{MossTare (g)}} \times 100$$

$$\text{Duff (\%)} = \frac{\text{DuffWet (g)} - \text{DuffDry (g)}}{\text{DuffDry (g)} - \text{DuffTare (g)}} \times 100$$

Equation 8. Change in gravimetric moisture content between repeated measures

$$\Delta \text{ Moss (\%)} = \text{Moss}_{t+1}\text{(\%)} - \text{Moss}_{t}\text{ (\%)}$$

$$\Delta \text{ Duff (\%)} = \text{Duff}_{t+1}\text{(\%)} - \text{Duff}_{t}\text{ (\%)}$$

Equation 9. Conversion of moss moisture to FFMC values (Wotton 2014b)

$$\text{FFMC} = 59.5 \times \frac{250 - \text{Moss}}{147.2 + \text{Moss}}$$

Equation 10. Conversion of upper-duff moisture to DMC values (Wotton 2014b)

$$\text{DMC} = 244.72 - 43.43 \times \ln(\text{Duff} - 20)$$

3 RESULTS AND DISCUSSION

After completing my experiments a few results emerged that are worthwhile to discuss. The lowland boreal forests research sites are shown in a photo collage (Figure 16), and then they are quantified in a structure and composition table (Table 6). Moss and upper-duff moisture content prior to sprinkler-watering and the weather during the sampling are graphed in Figure 17 and 18. Sprinkler-watering distribution was variable in lowland boreal forests due to partial obstruction by surrounding vegetation, in order to remove this variability; a control site was included to observe sprinkler-watering distribution without vegetation. When sprinklers were operated in absence of vegetation, there was a distinct spray pattern visible (Figure 19). The lowland boreal forests and sprinkler control experiments mean equivalent rainfall was 10 mm of sprinkler-watering per 3.8 L of gas, which took approximately 3 hours and 13 minutes to operate the system.

In lowland boreal forests, sprinkler-watering treatments moss and upper-duff moisture samples displayed a positive relationship (Figure 24), which increased to a point of diminishing return as fuel moisture values approached saturation levels (Figure 25). The observed relationship between sprinkler water distribution and fuel moisture changes led to the recommendation that moss and upper-duff receive at least 10 mm and 20 mm of equivalent rainfall. Given nonlinear regression Equations 17 and 18, this would change their fuel moisture content approximately 258% and 94% respectively. If the sprinkler spray distance is assumed 10 m, and recommended sprinkler-watering is 10 and 20 mm of equivalent rainfall, then each sprinkler would distribute 3,142 and 6,284 L of water. A longer sprinkler-watering duration causes moisture to seep deeper into soils for prolonged hydration. Moss moisture changed throughout the afternoon, and upper-duff moisture was impacted by bulk density and feather moss species. Lastly, research design and sampling limitations have been disclosed to provide context for the results and for improvements if the experiment was repeated.

3.1 Results

Vegetation found at lowland boreal forests sites is described both qualitatively and quantitatively. Fuel moisture levels prior to sampling and weather conditions during sampling are also examined in order to illustrate how they influence water absorption and retention. To predict fuel moisture changes a sprinkler-watering curve uses equivalent rainfall, and this relationship suggests the most efficient and recommended sprinkler-watering treatments for future application in lowland boreal forests. Samples were also further grouped into time sets to demonstrate the diurnal changes of moss. Both moss and upper-duff moisture changes were affected by bulk density, and upper-duff was affected by feather moss species. Overall, sprinkler-watering was able to modify fuel moisture beyond the point of ignition, but it took a longer watering duration to access deeper soils.

Forest Structure and Composition

Lowland boreal forests sites were assumed homogeneous in this study; however, at the tree stand scale they are more heterogeneous. Tree species within the forest type includes black spruce (*Picea mariana*) and white spruce (*Picea glauca*) with a minor component of poplar trees (*Populous spp.*), and understory vegetation included marsh labrador tea (*Ledum palustre*), lowbush cranberry (*Vaccinium vitis-idaea*), and blueberry (*Vaccinium uliginosum*). Sites selected in this study are shown in Figure 16, followed by a brief physical description of each area. Fort Wainwright sites 1 and 2 were removed due to above mentioned sprinkler malfunctions, causing experiment failure at those sites, therefore 6 sites were analyzed instead of the original 8. Poker Creek (LTER 2016) contained feather moss between mounds of grass scattered throughout the area, and between the mounds were pits, with some pits being deep enough to reach permafrost below. The Shaded Fuelbreak site had been recently thinned, removing many of the trees and shrubs while leaving behind withering moss for sampling. Beside the Shaded Fuelbreak site was the unmanaged Adjacent

Forest site, which had no thinning measures applied and therefore represented a similar forest in its natural state for comparison of stocking levels effect on water distribution and retention. Next was the Blueberry Bog site that contained abundant blueberry patches located at the edge of a bog. This site was followed by the Jenny Creek site that had an open canopy with a clumpy tree distribution; the presence of cloudberry (*Rubus chamaemorus*) herb was unique because it was not noticed at other sites. Eielson was the last site sampled, and it had both the largest trees with the greatest abundance of shrubs. These anecdotal observations are combined with quantitative site covariates that document structure and composition of lowland boreal forests sites and samples.

Lowland Boreal Forests Research Sites

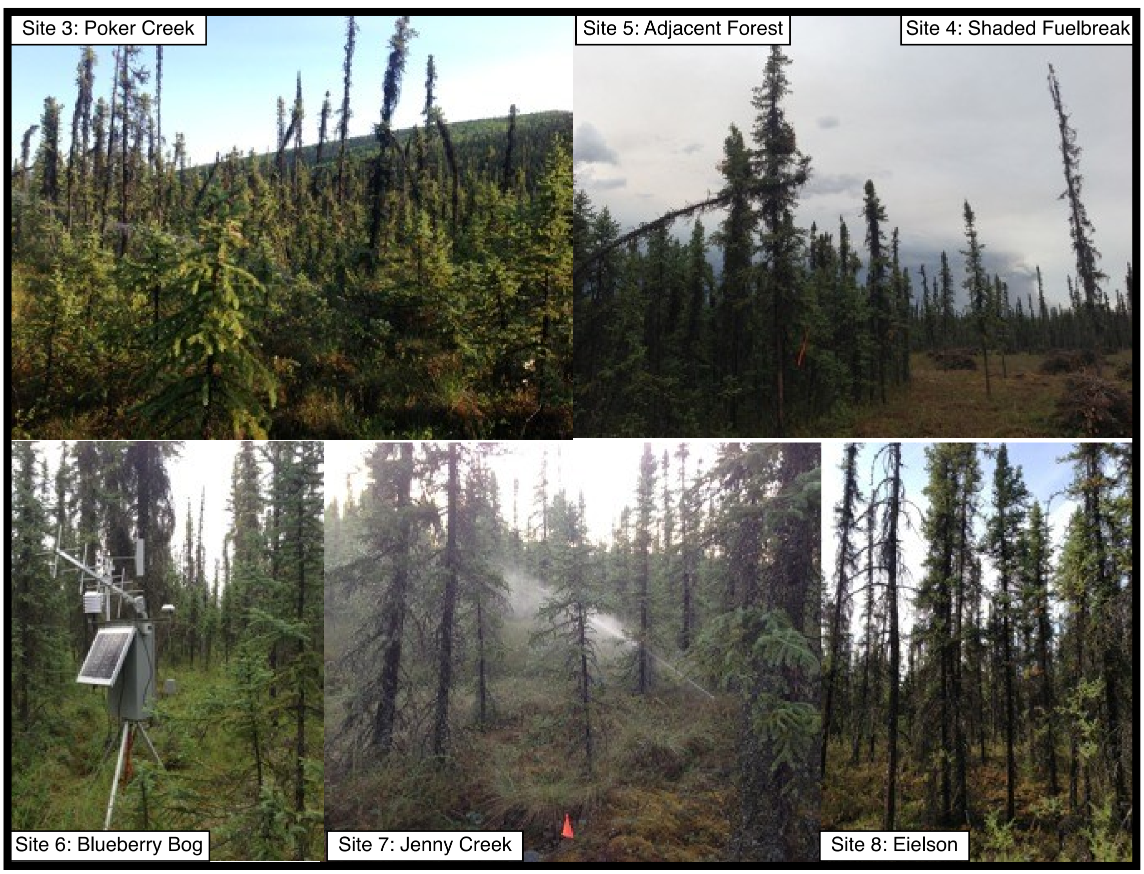


Figure 16. Site photos showing lowland boreal forests structure and composition.

Lowland boreal forests structure and composition shown in Table 6 could influence sprinkler-watering distribution and fuel moisture changes between sites and samples. Excluding the Shaded Fuelbreak site because it was artificially thinned; the average stocking density was 1 tree per 3.25 m^2; and the mean tree diameter at each site ranged from 3.6 to 10.4 cm at 1.3 m height; however, poplar trees may have skewed diameter averages because they usually grow faster than spruce trees. The estimated tree height ranged from 6 to 15 m among sites, and the majority of locations had an open canopy, with the average canopy closure of 40% when excluding the Shaded Fuelbreak. In terms of feather moss species, composition was tallied as a count of the 48 sample locations established at each site, and mean bulk density was also calculated and recorded. These site and sample environmental factors could affect sprinkler-watering distribution and resulting moss and upper-duff moisture changes.

Table 6. Lowland boreal forest structure and composition for each site

Lowland Boreal Forests Structure and Composition

Site	Nearest Tree Species (count)	Stocking (m^2/tree)	Canopy Closure (%)	Tree Height (m)	Tree DBH (cm)	Moss Species (count)	Bulk Density (kg/m^3)
Poker Creek	Spruce (35)	4.08	35	9	4.0	PleSch (48)	Moss = 23.49 Duff = 39.79
Shaded Fuelbreak	Spruce(5), Poplar(2)	42.36	6	6	10.4	HylSpl (19), Mix (3), PleSch (26)	Moss = 28.03 Duff = 49.39
Adjacent Forest	Spruce (47)	1.51	36	8	4.0	HylSpl (32) PleSch (4) Mix (12)	Moss = 26.18 Duff = 38.78
Blueberry Bog	Spruce(44), Poplar(1)	1.97	54	13	5.7	HylSpl (40) Mix (5) PleSch (3)	Moss = 21.11 Duff = 33.42
Jenny Creek	Spruce (30)	5.91	30	8	3.6	PleSch (48)	Moss = 24.73 Duff = 29.68
Eielson	Spruce (43)	2.79	43	15	7.9	HylSpl (38) Mix (5) PleSch (5)	Moss = 23.82 Duff = 29.96

Fuel Hazard

Fuel moisture contents both before and after sprinkler-watering treatments were paramount to the results of this experiment. The 2013 summer when this experiment was conducted was very hot, making fuels dry and ideal for testing sprinkler-watering treatments. The boxplot shown in Figure 17 illustrates fuel moisture at each site was either near or beyond the ignition threshold prior to sprinkler-watering. Larger boxes indicate a greater degree of variation, which can be associated with damper fuel, conversely when drought conditions occur, moisture begins to equalize among samples, and this is important to the resulting data because drier fuels absorb more moisture. A heat colour ramp illustrates the seasonal trend of the drought code rising throughout summer. Fuel moisture changes between repeated measures will be monitored using the control samples to compare sprinkler-watering treatments' fuel hazard reduction.

Fuel Hazard Before Sprinkler-watering

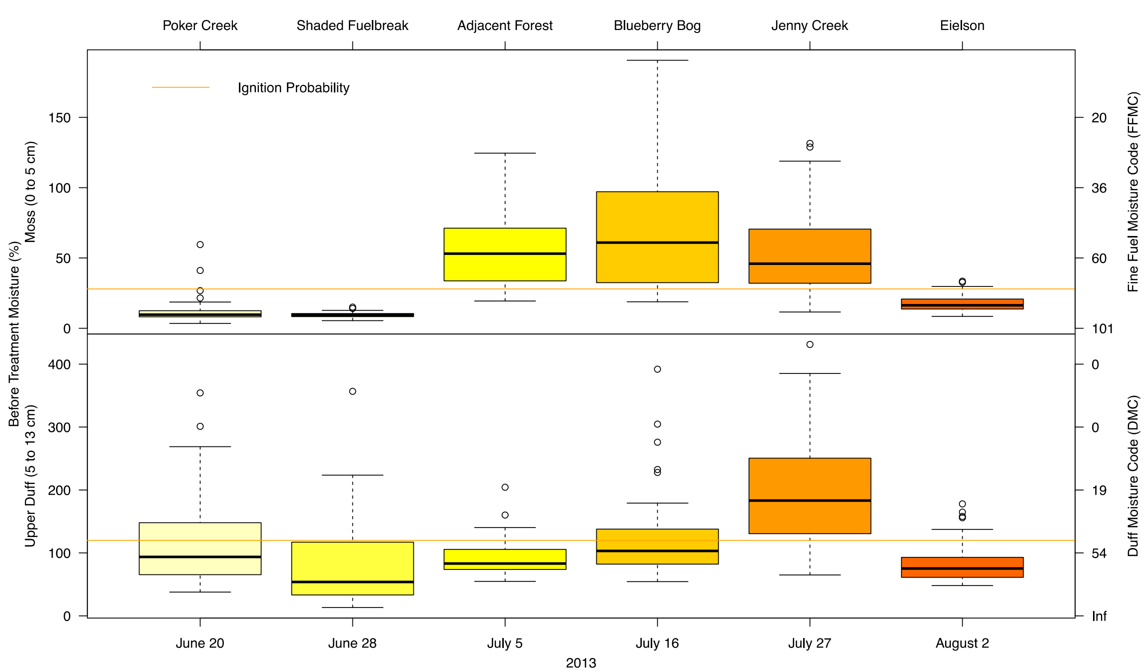


Figure 17. Sites' fuel moisture content prior to sprinkler-watering treatment.

Weather Conditions

Weather represented a significant variable during the sampling process since it influences fuel moisture adsorption and retention; therefore, weather changes between repeated measures were monitored with a RAWS. In this capacity, Figure 18 graphs hourly temperature (^{o}C), relative humidity (%), wind speed (km/hr.) and solar radiation (kW/m^{2}) during testing from 12:00 to 18:00 the following day for each site. If appreciable precipitation (mm) was captured in the rain tipping-bucket or control plots, then equivalent rainfall bars could be added to the weather graph’s base. Visualizing weather patterns for each site provides context about how weather conditions may influence fuel moisture changes.

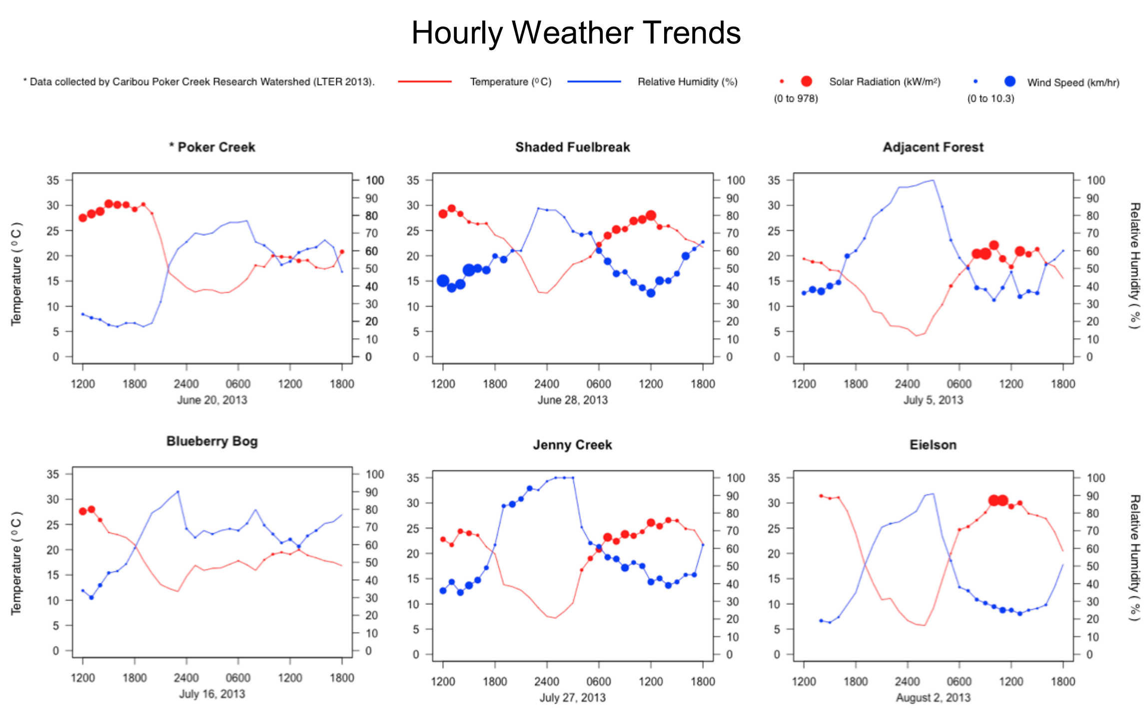


Figure 18. Hourly weather data was collected using a Remotely Automated Weather Station (RAWS) at each site.

Sprinkler-watering Distribution

Sprinkler-watering distribution levels were tested in lowland boreal forest sites and at a control experiment as outlined above. If sprinkler-watering duration increases, then sprinkler-watering distribution increases correspondingly. In this capacity, water distribution levels achieved are directly related to amount of gas consumed by the water pump, which itself expresses sprinkler-watering duration and thereby increases equivalent rainfall. Figure 19 illustrates equivalent rainfall amounts based upon the sample distance from sprinklers. Sprinkler-watering distribution in the lowland boreal forest sites was more varied than the sprinkler control site due to the vegetation present. The control sprinkler site was a flat gravel area, which contained no vegetation; samples were spaced 1 m apart along the plot radius at 2 plots to test water distribution, and to compare with lowland boreal forests distribution sites. It took approximately 3 hours and 13 minutes for a water pump to consume 3.8 L of gas, which sprayed 10 mm of equivalent rainfall across the plot. If the plot radius is 10 m, then the plot area is 314.15 m^2, and 10 mm of equivalent rainfall would distribute approximately 3,142 L of water. Understanding sprinkler-watering distribution helps in planning the sprinkler-watering treatment needed to reduce the likelihood of wildfires.

Sprinkler-watering Distribution

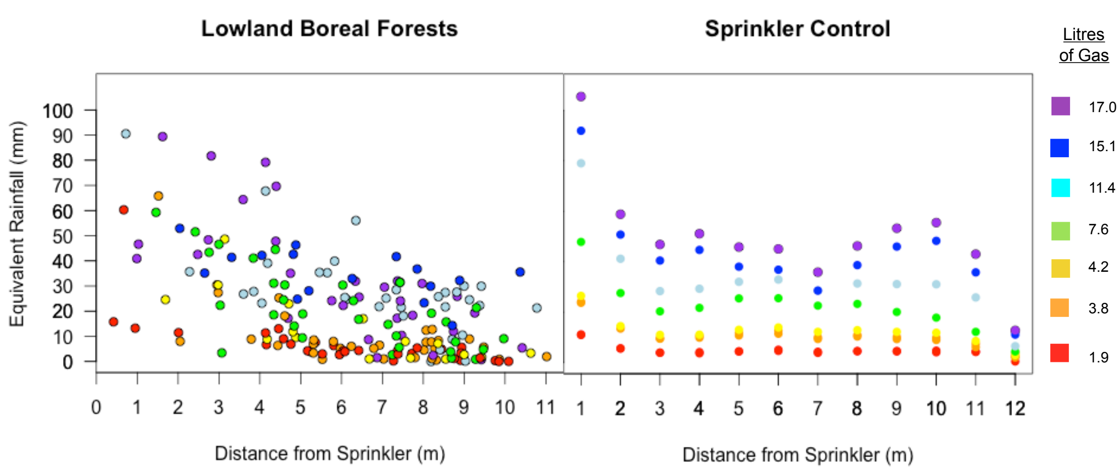


Figure 19. Lowland boreal forests and control sprinkler site equivalent rainfall levels plotted according to distance from sprinkler and litres of gas applied.

The sprinkler-watering equivalent rainfall data was interpolated to represent 3.8 L of gas proportions in order to create a unit measure for linear regression. The type and strength of the relationship between equivalent rainfall and distance from sprinkler was determined using Pearson's correlation (r) values. At the lowland boreal forest sites and sprinkler control site the Pearson coefficient was -0.57 and -0.70 respectively and p-values were 2.2^{-16}, which implies equivalent rainfall values decreased according to their respective distance from the sprinkler. Since both r-values partially explained data variation, their linear Equation 11 and Equation 12 were formulated to provide general estimates for sprinkler-watering distribution: x-axis was distance from sprinkler and y-axis was equivalent rainfall.

Equation 11. Lowland boreal forests watering distribution levels

Lowland Boreal Forests ($r^2 = 0.32$) $$y_{rain} = 27.146 - 2.696\ x_{distance}$$

Equation 12. Sprinkler control site watering distribution levels

Sprinkler Control Site ($r^2 = 0.48$) $$y_{rain} = 16.8382 - 0.9477\ x_{distance}$$

The lowland boreal forests linear equation had a greater slope coefficient and y-intercept than the sprinkler control equation; this suggests a larger range of equivalent rainfall data, which is also reflected by the lower R^2 values. Sample location within a 5 m radius of the sprinkler at the lowland boreal forests sites had greater concentrations of equivalent rainfall than what was observed at the control site, which is likely an effect of vegetation in close proximity blocking and accumulating the sprinkler's spray. This suggests vegetation plays an important role in the determining the operational efficacy of sprinkler-watering distribution and should therefore be considered when selecting the site for sprinkler setup.

Fuel Moisture Changes

Moss and upper-duff moisture content levels were separated according to control and watering treatment groups in the results because they demonstrated divergent trends. In Figure 20, gravimetric fuel moisture content before and after sprinkler testing are shown, and a 1:1 line was drawn to illustrate no fuel moisture change between repeated measures. As depicted, the majority of control samples were below the 1:1 line because they lost moisture between repeated measures, and sprinkler-watering samples were mostly above the 1:1 line because they gained moisture, except for the sample locations that were blocked by vegetation. To illustrate moss and upper-duff ignition potential, orange lines were drawn at the 28% and 120% moisture content, which represent the respective fuel hazard thresholds to prevent ignition for moss and upper-duff respectively. The majority of moss watering samples examined would not support combustion; however, many upper-duff samples remained susceptible to fire. Control site samples provided a benchmark of fuel moisture changes between repeated measures for comparing fuel hazard outcomes. These results represent the potential viability of sprinkler-watering treatment as a defense mechanism.

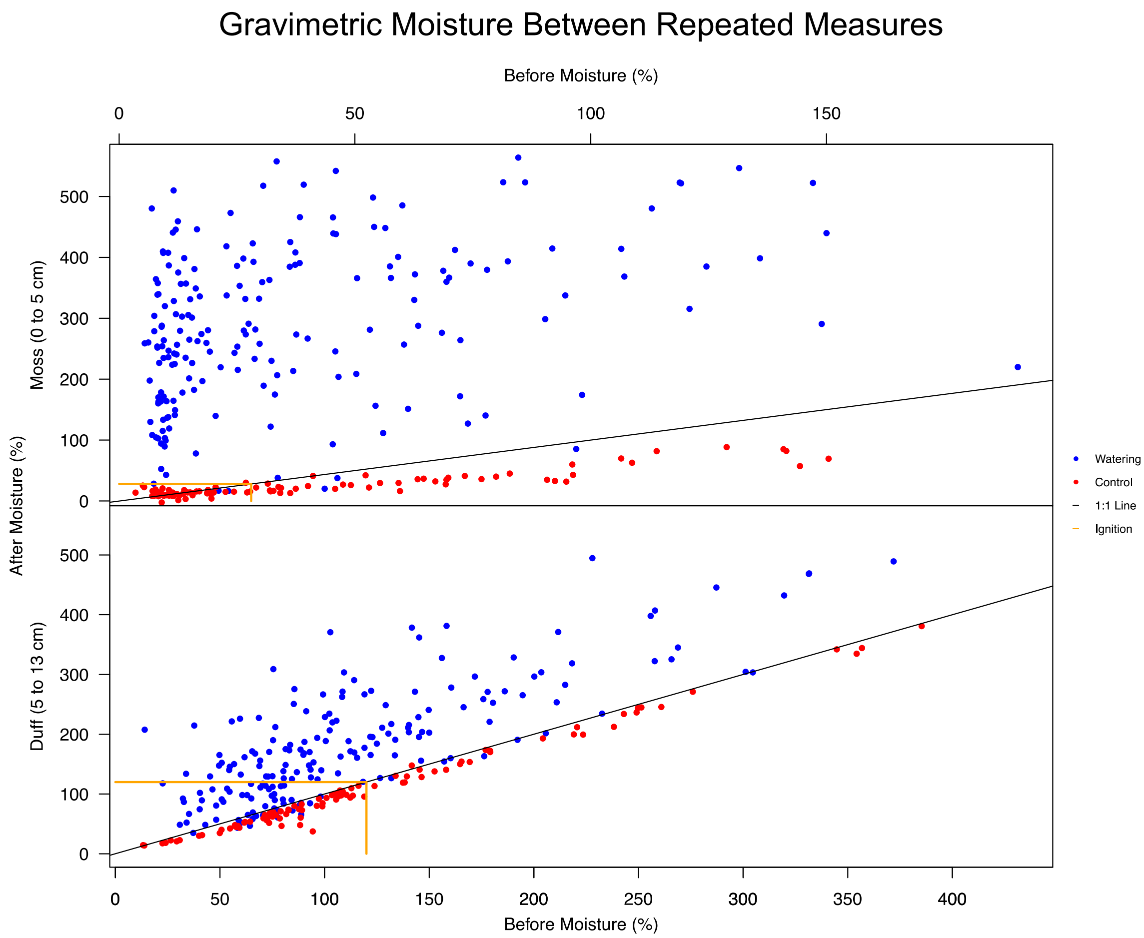


Figure 20. Moss and upper-duff fuel moisture levels before and after treatment.

For the purposes of this study, sprinkler-watering treatment effect represents the identifiable change in fuel moisture content between repeated measures. A paired t-test in Table 7 detected whether changes in treatment groups according to their fuel moisture content were significant. All the treatment groups rejected the null hypothesis that there were no significant fuel moisture changes between repeated measures with a p-value less than 0.01, and this means that the moisture content changes were significantly affected by the treatments applied. The moss and upper-duff mean moisture changes were 250% and 73% for sprinkler-watering, while naturally occurring drying (desorption) were -15% and -12% loss respectively. The 95% confidence intervals describe the range in moisture values around the mean, providing broad-based estimates in fuel moisture changes between repeated measures.

Table 7. A paired t-test of moisture changes between repeated measures of sprinkler-watering and control treatments. Yellow highlighted p-values indicate fuel moisture changes were significantly different between repeated measures

Daily Repeated Measures Paired T Test

Response Variable: Moss Moisture Changes (%)

Source	df	t-value	p-value	Mean	95% Confidence Intervals	
Watering	191	27.83	< 2.2e-16	250.44	232.69	268.19
Control	95	-6.96	< 4.5e-10	-15.18	-19.51	-10.85

Response Variable: Upper Duff Moisture Changes (%)

Source	df	t-value	p-value	Mean	95% Confidence Intervals	
Watering	191	14.81	< 2.2e-16	73.25	63.49	83.01
Control	95	-13.58	< 2.2e-16	-11.77	-13.49	-10.05

Since sprinkler-watering duration levels varied between sites, it is difficult to draw exact comparisons between research sites. This study assumes that all lowland boreal forest sites are relatively homogeneous, although, covariate data was collected to explain and account for circumstantial results that challenge this assumption. In this capacity, Figure 21 shows each site's fuel moisture changes, including their 90% confidence intervals for each sprinkler-watering treatment. It is clear that even small amounts of water changes fuel moisture levels tremendously, and the y-axis reveals that moss had a greater magnitude of moisture change than upper-duff samples. However, an analysis of variance test (ANOVA) will explicitly determine and demonstrate whether sprinkler-watering treatment does in fact significantly affect change in fuel moisture values.

Lowland Boreal Forests' Sprinkler-watering Treatments

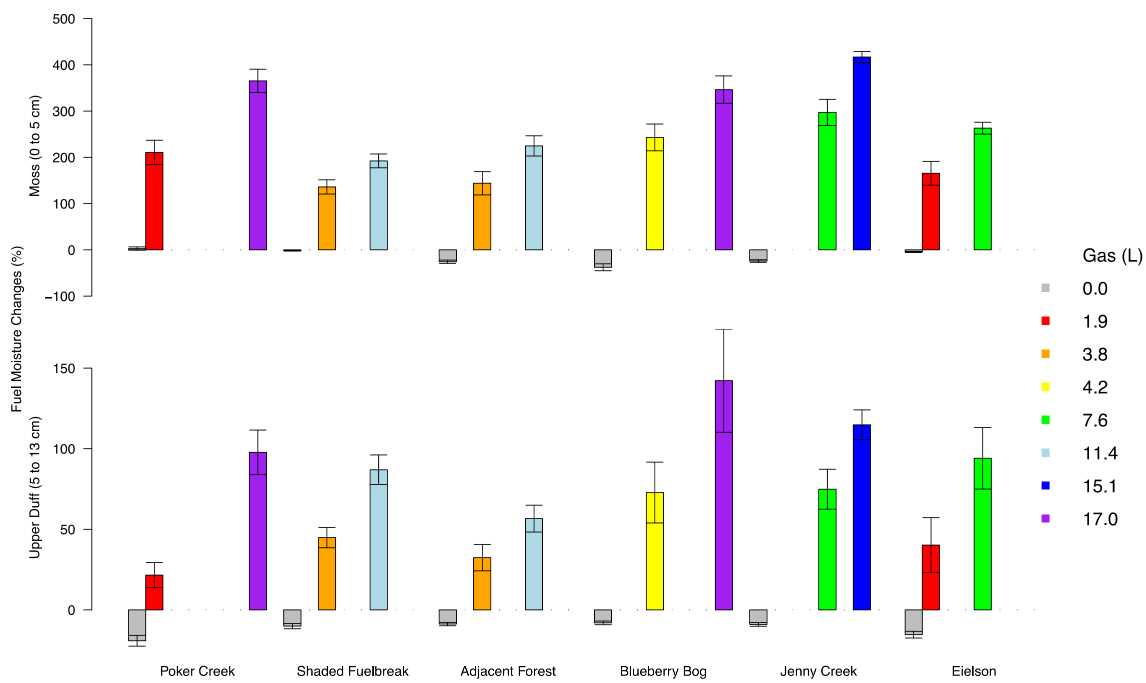


Figure 21. Sprinkler-watering treatment fuel moisture changes at each site.

ANOVA testing must satisfy the following assumptions: Independence of sample units, normal distribution, and equal variance of residuals. The independence of the samples collected was achieved through spatial and temporal randomization within a treatment plot; described in the above methodology. However, a third of the samples did not receive sprinkler-watering because of the inclusion of control treatment plots at each site (see Figure 9); this caused a disproportionate emphasis on control treatments in the sample population. Figure 22 depicts moss's bimodal distribution as rebalanced to show the sprinkler-watering treatment's normal distribution, and the residuals plot confirms equal variance of experimental error. To rebalance the bimodal distribution, control samples were omitted, leaving a normal distribution of the watering treatment levels as shown in the Kernel Density and Q-Q plots. A Shapiro-Wilk's tested a priori level (α) of 0.05, and the result was a p-value of 0.08, confirming that the samples did not deviate from normality. Equal variance of residuals also appeared relatively uniform except for a few outliers identified.

Homoscedasticity was confirmed using the Levene's Test at a priori level (α) of 0.05 to produce a p-value of 0.82, meaning equal variance of residuals was achieved. Given the above results, moss watering samples met the ANOVA assumptions for testing sprinkler-watering duration impact on moisture changes.

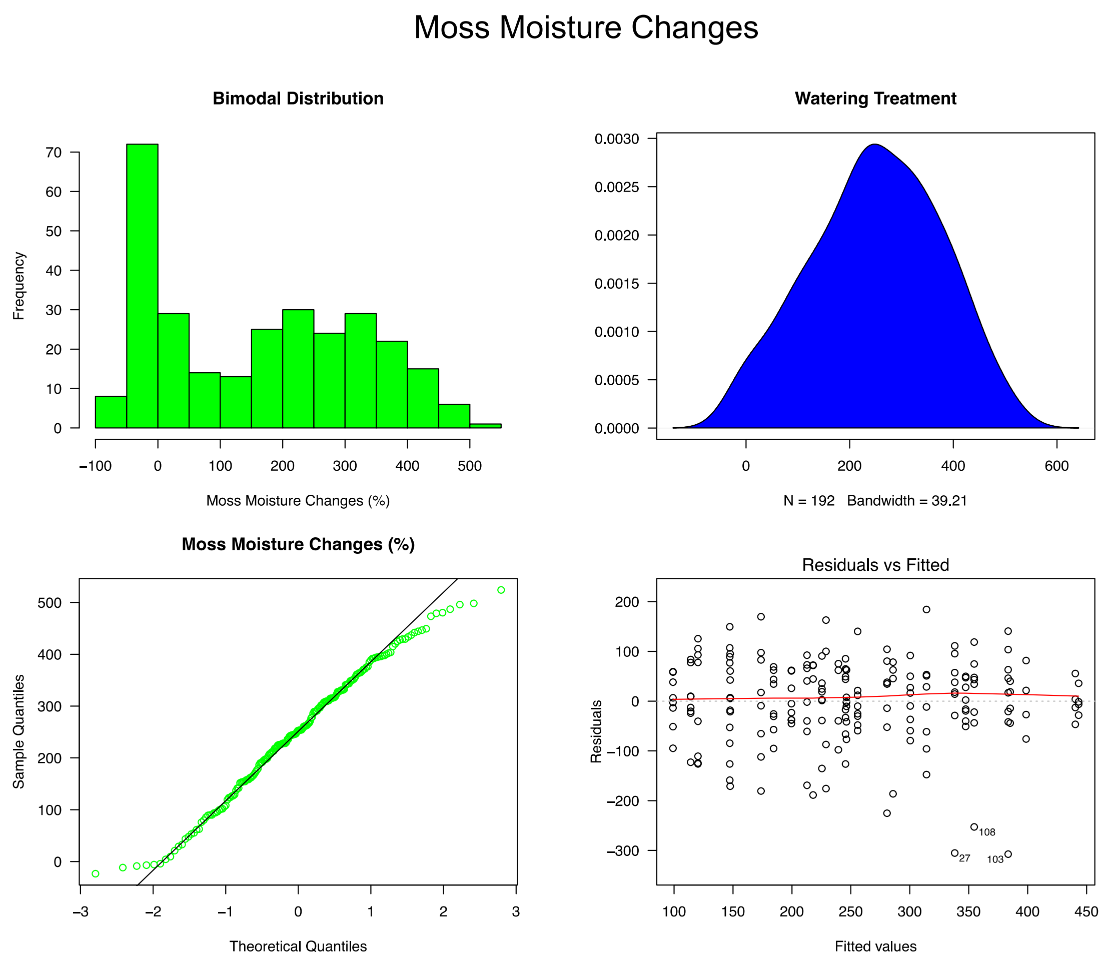


Figure 22. Histogram (top left) of moss moisture changes including control samples. Kernel density (top right) distribution of sprinkler-watering samples. A Q-Q plot (bottom left) showing variance of sprinkler-watering moisture changes. The fitted residuals (bottom right) plot shows variance amongst sprinkler-watering residuals.

Similar to moss, upper-duff bimodal distribution was rebalanced by removing control samples as shown in Figure 23. The changes observed in upper-duff moisture levels were calculated for analysis using Equation 13 to shift and smooth the data distribution as illustrated in the Kernel Density plot. Since some sprinkler-watering samples lost moisture between repeated measures, it is presumed these samples were either blocked by vegetation or sheltered by feather moss. In order to shift all upper-duff moisture changes into positive values, 24% was added to the samples, as well, to smooth an imperfection an exponent of 0.4 has been used to compress the range of values. The Shapiro-Wilk’s test was used to determine if the transformed upper-duff moisture changes produced a normal distribution at a priori level (α) of 0.05, a p-value of 0.051 indicates the distribution barely qualified as normal. Visually, the Q-Q plot follows the Q-Q line except for dipping below the first negative standard deviation. To assess homoscedasticity, the Levene’s Test was used at a priori level (α) of 0.05 and this resulted in a p-value of 0.07, thereby indicating an equal variance. Thus, an ANOVA test of sprinkler-watering is possible because transformed upper-duff moisture changes have a normal distribution and equal variance of residuals.

Upper-duff Moisture Changes

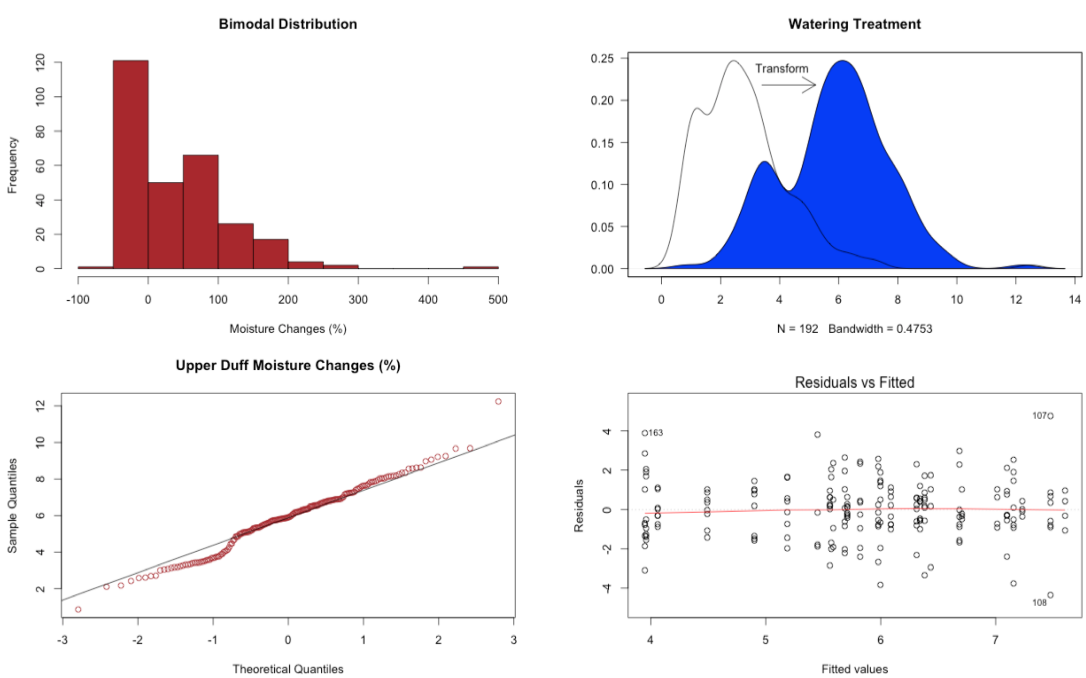


Figure 23. Histogram (top left) of upper-duff moisture changes. Kernel density (top right) distribution of sprinkler-watering samples before and after transformation. A Q-Q plot (bottom left) showing variance of sprinkler-watering moisture changes. The fitted residuals (bottom right) plot shows equal variance amongst sprinkler-watering residuals.

Equation 13. Upper-duff watering treatment group transformation

$$\text{Transform} = (\text{DuffChanges} + 24)^{0.4}$$

A linear model is written in Equation 14 to evaluate sprinkler-watering effect on fuel moisture changes over repeated measures from 1200 to 1900.

Equation 14. A sprinkler-watering treatment's moisture change for a time set

$$\mathrm{Y_{wtr}} = \mu + \mathrm{G_w} + \mathrm{B_t} + \mathrm{GB_{wt}} + \varepsilon_{\mathrm{wtr}}$$

Where: Y_{wtr} was fuel moisture changes between repeated measures; and
$\varepsilon_{\mathrm{wtr}}$ was residual error between sample replications.

Null Hypotheses:

H_0: No difference in means at any sprinkler-watering treatment levels (G_w).

H_0: No difference in means time set blocks (B_t).

H_0: No difference in means between sprinkler-watering and time set (GB_{wt}).

Alternative Hypotheses:

H_1: Sprinkler-watering treatments (G_w) caused a difference in moisture changes.

H_1: Time set (B_t) caused a difference in moisture changes.

H_1: Sprinkler-watering and time set (GB_{wt}) caused a difference in moisture changes.

All the rejected null hypotheses were further studied to explore their alternative hypothesis. Additionally, bulk density and feather moss species are analyzed to assess if they affected the moss and upper-duff moisture changes during testing.

This experiment tested whether sprinkler-watering duration significantly affected moss and upper-duff moisture changes throughout the time sets. Table 8 ANOVA results rejects the null hypothesis for moss and upper-duff when tested at a piriori (∝) level of 0.01; therefore, sprinkler-watering was effective at positively changing moss and upper-duff moisture values. Moreover, moss time sets were also significant at the piriori (∝) level of 0.1, and no interaction effect was found between moss watering duration and time sets.

Table 8. ANOVA test for the sprinkler-watering treatments blocked by time sets. Yellow highlighted p-values were significant and required further investigation

Sprinkler-watering ANOVA

Response Variable: Moss Moisture Changes (%)

Source	df	Sum of Squares	Mean of Squares	F-Value	p-value
Watering (Gw)	6	1,399,197	233,200	28.9002	< 2.e-16
Time Set (Bt)	3	63,358	21,119	2.6173	0.053
Interaction (GBwt)	18	184,039	10,225	1.2672	0.216
Error (εwtr)	164	1,323,340	8,069		

Response Variable: Transformed Upper Duff Moisture Changes (%)

Source	df	Sum of Squares	Mean of Squares	F-Value	p-value
Watering (Gw)	6	151.24	25.2064	10.2816	< 1.182e-09
Time Set (Bt)	3	10.87	3.625	1.4786	0.222
Interaction (GBwt)	18	37.88	2.1043	0.8583	0.629
Error (εwtr)	164	402.06	2.4516		

The 4 four samples within each treatment plot were averaged to calculate plot means, and then all samples retrieved within a treatment level were averaged to calculate the grand mean. Figure 24 graphs both plot and grand means of moss and upper fuel moisture changes, and standard error of the mean bars indicates the range of treatment means. Moss and upper-duff moisture changes were positively affected by sprinkler-watering treatments as indicated by Pearson’s correlation (r) values of 0.85 and 0.78 respectively, and the relationships were strong. Equation 15 and 16 estimate the moss and upper-duff moisture changes given a specified amount of gas is available. Clearly, moss was more reactive to sprinkler-watering than upper-duff samples, and this prevailing outcome was indicated by the greater slope coefficient in the linear equation. As well, the y-intercept suggests no gas produces positive moistures changes, which is obviously inaccurate because no sprinkler-watering caused moisture loss as shown in the control samples; thus, a nonlinear regression equation might better match the relationship between moisture changes and gas.

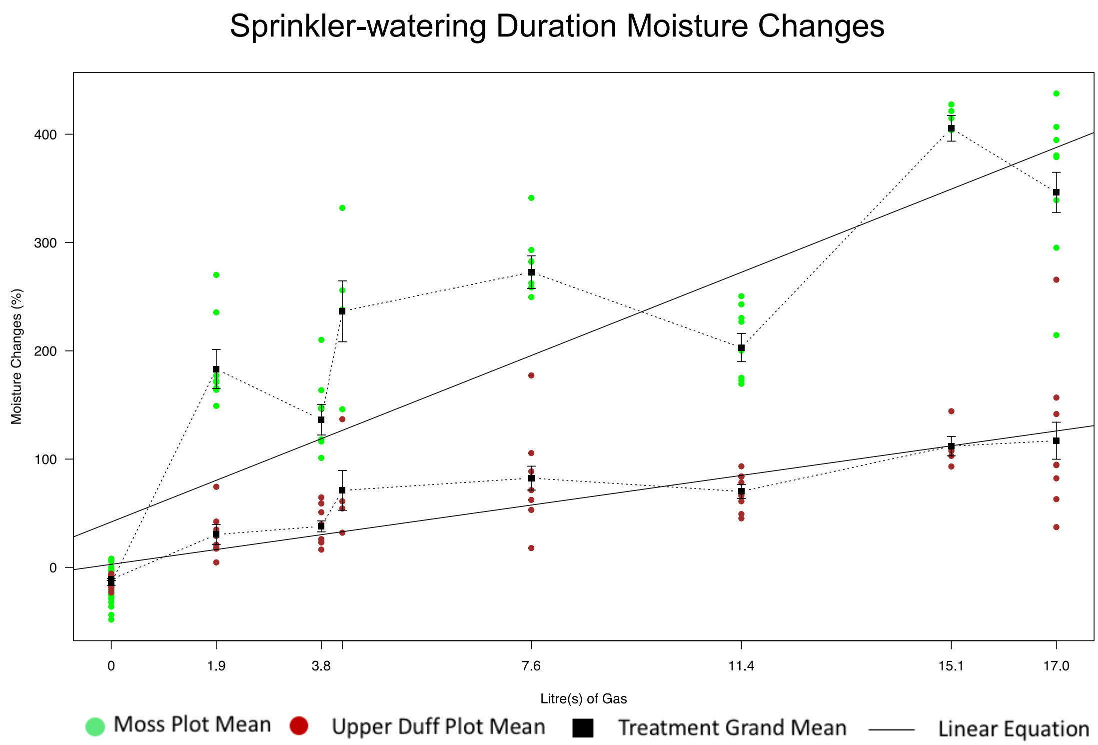


Figure 24. Moisture changes plot means and grand mean for moss and upper-duff samples.

Equation 15. Moss moisture changes as per the litres of gas used

Moss ($r^2 = 0.72$) $y_{moisture} = 79.07\ x_{gas} + 42.86$

Equation 16. Upper-duff moisture changes as per the litres of gas used

Upper-duff ($r^2 = 0.61$) $y_{moisture} = 2.512\ x_{gas} + 28.162$

Sprinkler-watering Curve

Instead of fixed sprinkler-watering duration levels, equivalent rainfall values were a continuous factor to quantify sprinkler-watering treatment on the x-axis. Mean water container weight was converted into equivalent rainfall using Equation 6 to plot the fuel moisture changes on a continuum. A dot plot in Figure 25 displays the relationship between equivalent rainfall and moss and upper-duff moisture changes, which is a fairly strong relationship as indicated Pearson's Correlation (r) values 0.71 and 0.73 and a p-value of less than 0.01, meaning a sprinkler-watering curve could estimate moss and upper-duff moisture changes using equivalent rainfall. Therefore, nonlinear regression used equivalent rainfall as a predictor for fuel moisture changes in moss and upper-duff samples in order to formulate a sprinkler-watering curve as demonstrated in Equation 17 and 18.

Water use efficiency (WUE) is the maximum moisture change observed for the minimum amount of equivalent rainfall. Therefore, it can be expressed as a ratio of the amount of moisture changes divided by the amount of equivalent rainfall shown in Equation 19. Using Microsoft Excel Solver tool this ratio was maximized by changing the amount of water applied to determine 1 mm and 5 mm of equivalent rainfall to be the most efficient use of water for moss and upper-duff samples. These efficiency values might be suitable for surface fuel system, in water-limited environments, or during limited response time situations. Nevertheless, recommended sprinkler-watering is at least 10 mm and 20 mm of equivalent rainfall for moss and upper-duff because after this point moisture changes begin to plateau as shown in Figure 25. If the 10 mm and 20 mm of equivalent rainfall are calculated using sprinkler-watering curve Equations 17 and 18, then moss and upper-duff moisture levels are predicted to increase by 258% and 94% respectively. These findings can help sprinkler protection programs to plan watering treatment levels when utilizing sprinklers in wildfire operations.

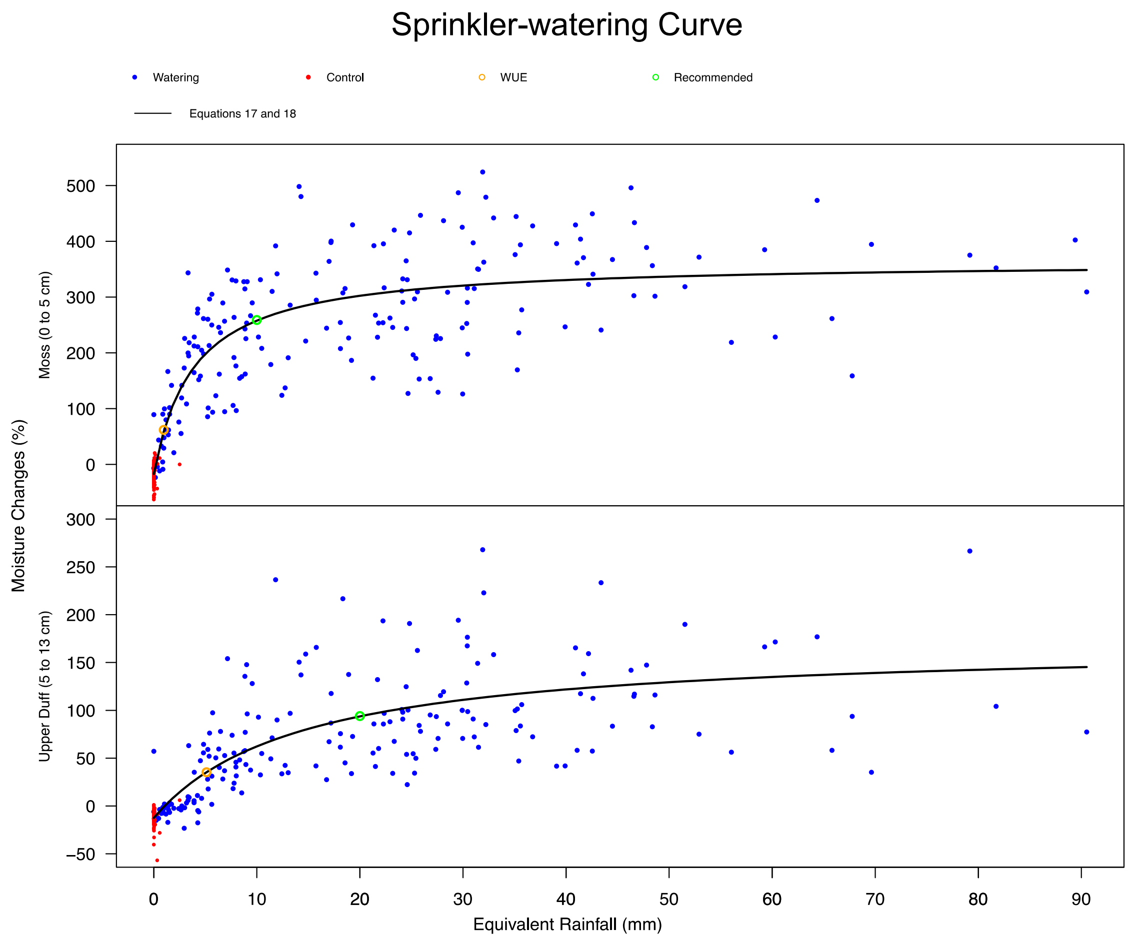


Figure 25. The sprinkler-watering curve estimates fuel moisture changes according to equivalent rainfall, circles show WUE and recommended treatments.

Equation 17. Sprinkler-watering curve for moss (0-5 cm) samples

$$\text{Moss (\%)} = 364.156 + \left(\frac{-1476.139}{\text{Rain} + 3.872}\right)$$

Equation 18. Sprinkler-watering curve for upper-duff (5-13 cm) samples

$$\text{Duff (\%)} = 170.41 + \left(\frac{-2644.49}{\text{Rain} + 14.46}\right)$$

Equation 19. Water use efficiency ratio (WUE) for moss or upper-duff samples

$$WUE_{moss} = \frac{Moss\ (\%)}{Rain\ (mm)} \qquad WUE_{duff} = \frac{Duff\ (\%)}{Rain\ (mm)}$$

Time Sets

In this experiment, time of each sample was recorded over repeated measures to illustrate afternoon and daily trends. Figure 26 demonstrates that sprinkler-watering treatments effectively changed the majority of moss moisture beyond ignition and approximately half of the upper-duff samples too.

Afternoon Moisture Trends

Figure 26. Moss and upper-duff moisture content levels before and after sprinkler-watering, a horizontal line indicates ignition probability threshold.

Since moss moisture changes were significantly affected by the time sets, a box plot in Figure 27 shows sample distribution for control and watering treatment groups. The control treatments moisture changes remain relatively stable through the time sets, while sprinkler-watering mean moistures changes indicate a decline between time sets as samples become more variable as they dry during the afternoon. As expected, moss samples were influenced by drying conditions throughout the afternoon hours, making time sets a valuable factor in this study. Lastly, control treatments lost moisture, and this left fuels susceptible to wildfires; however, sprinkler-watering often raised moisture beyond possible ignition.

Moss Moisture Changes

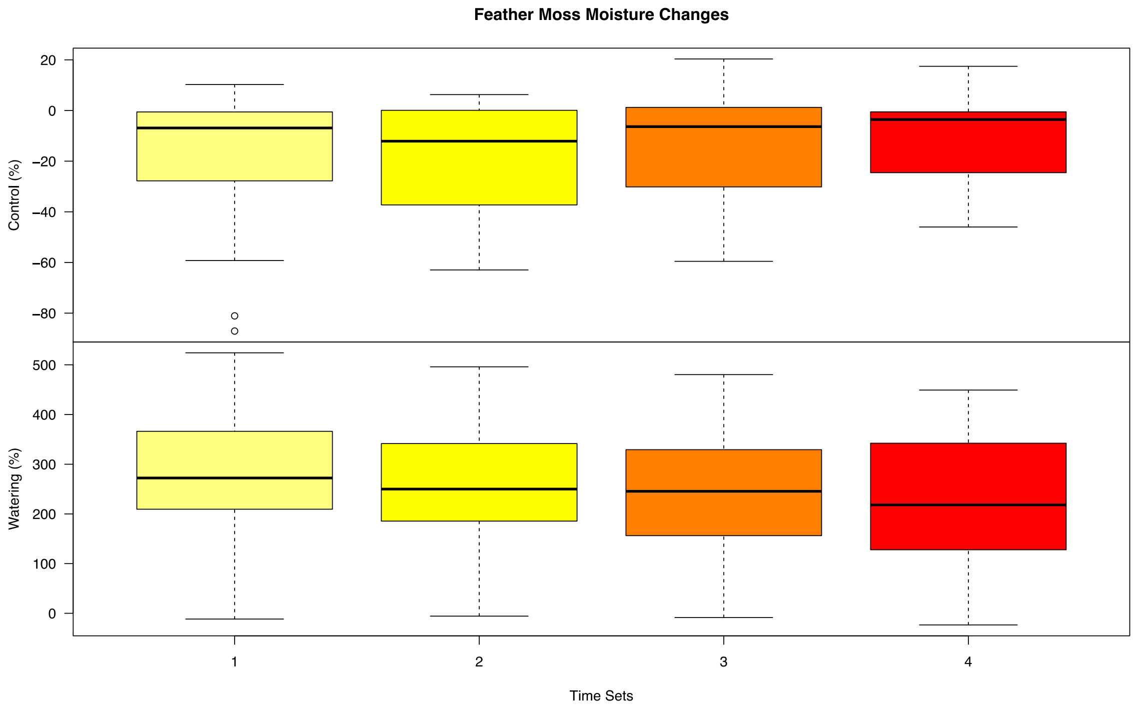


Figure 27. Control treatment and sprinkler-watering moss moisture changes for each time set throughout the afternoon.

When time sets are averaged and examined in treatment groups over multiple days, upper-duff moisture changes become apparent. Figure 28 shows the time sets utilized for moss and upper-duff sample sites Blueberry Bog, Jenny Creek, and Eielson as collected over multiple days. On day 3, no samples were taken at the Eielson site due to rainfall that could confound the treatment effect. As previously mentioned, sprinkler-watering treatment prevented feather moss from reaching ignition levels over multiple days, while upper-duff sprinkler required at least 21.2 mm of equivalent rainfall to achieve this same hazard reduction. In contrast, the control samples show that fuels were susceptible to ignition and tracked atmospheric moisture exchanges between time sets.

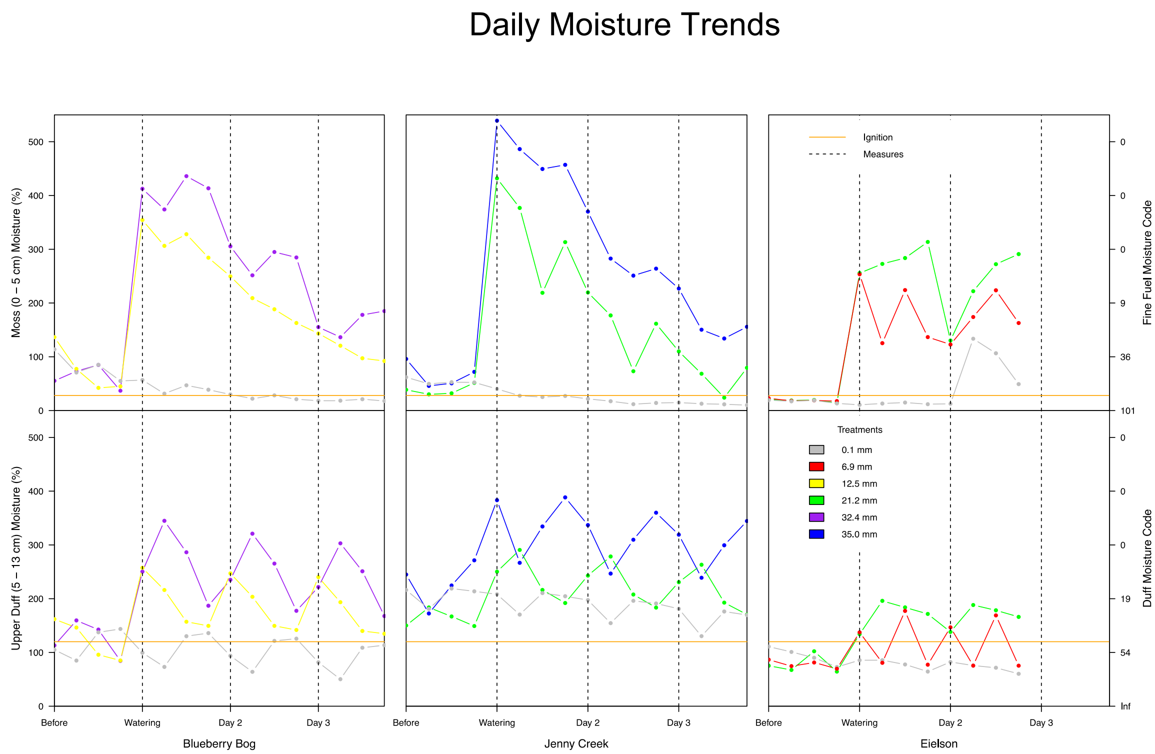


Figure 28. Treatment mean time set values for daily repeated measures for 3 sites over multiple days (Blueberry Bog, Jenny Creek, and Eielson).

Bulk Density

It was also hypothesized that moisture changes are positively influenced by bulk density, ANCOVA assess its effects on fuel moisture changes. As displayed in Table 9, bulk density rejected the null hypothesis with a p-value of 0.02 and 0.03 for moss and transformed upper-duff respectively, supporting the alternative hypothesis that fuel moisture changes are affected by bulk density. A greater bulk density resulted in lower moisture changes, however, fuel moisture changes can be a misleading metric because they are relative to their oven-dried weights, and upper-duff weights were roughly twice as heavy as moss samples.

Table 9. A covariate analysis of bulk density effects on fuel moisture changes. Yellow highlighted p-values indicate that moss and upper-duff were significantly affected by bulk density.

Bulk Density ANCOVA

Response Variable: Moss Moisture Changes (%)

Source	df	Sum of Squares	Mean of Squares	F-Value	p-value
Watering (Gw)	6	1,399,197	233,200	30.0097	2E-16
Time Sets (Bt)	3	63,358	21,119	2.7178	0.04642
Bulk Density	1	44,721	44,721	5.755	0.01757
Interaction (GBwt)	18	196,025	10,890	1.4014	0.13691
Error (εwtr)	163	1,266,643	7,771		

Response Variable: Transformed Upper Duff Moisture Changes (%)

Source	df	Sum of Squares	Mean of Squares	F-Value	p-value
Watering (Gw)	6	151.24	25.2064	10.3953	9.567e-10
Time Sets (Bt)	3	10.87	3.625	1.495	0.21791
Bulk Density	1	12.21	12.2124	5.0365	0.02617
Interaction (GBwt)	18	32.49	1.8048	0.7443	0.76126
Error (εwtr)	163	395.24	2.4248		

Feather Moss Species

It was hypothesized that feather moss species might affect fuel moisture change, to evaluate its effect samples were categorized by species, and the analysis of covariance (ANCOVA) in Table 10 tested their impact on moisture. Feather moss species p-value of 0.65 failed to reject the null hypothesis at priori level (α) of 0.1 meaning feather moss species had no effect on moisture changes. Alternatively, transformed upper-duff moisture changes p-value of 0.08 was below priori level (α) of 0.1, this suggests that moss species affected upper-duff moisture changes. Further research might explain feather moss's effect on fuel moisture changes in upper-duff, possibly delving into soil succession.

Table 10. A covariate analysis of moss species influences on fuel moisture changes: The yellow highlighted p-value shows transformed upper-duff moisture changes (%) were significantly affected by feather moss species for a priori value (α) of 0.1

Feather Moss Species ANCOVA

Response Variable: Moss Moisture Changes (%)

Source	df	Sum of Squares	Mean of Squares	F-Value	p-value
Watering (Gw)	6	1,399,197	233,200	28.6455	2e-16
Time Set (Bt)	3	63,358	21,119	2.5942	0.054
Species	2	6,959	3,480	0.4274	0.653
Interaction (GBwt)	18	181,608	10,089	1.2393	0.236
Error (εwtr)	162	1,318,822	8,141		

Response Variable: Transformed Upper Duff Moisture Changes (%)

Source	df	Sum of Squares	Mean of Squares	F-Value	p-value
Watering (Gw)	6	151.24	25.2064	10.4356	8.997e-10
Time Set (Bt)	3	10.87	3.625	1.5008	0.216
Species	2	12.35	6.1773	2.5574	0.081
Interaction (GBwt)	18	36.29	2.0159	0.8346	0.658
Error (εwtr)	162	391.30	2.4154		

3.2 Discussion

In the following section, the results of this study will be discussed with specific regards to tactics that can be used to enhance wildfire operations. As noted in the above results, sprinkler-watering distribution levels achieved in this experiment were influenced by watering duration and vegetation interfering with the spray trajectory. A control site containing no vegetation was introduced and studied to compare sprinkler spray range and efficacy as described below. Overall, this research suggests that sprinkler protection programs could hydrate hazardous fuels to raise moisture values thereby preventing their ignition. Although, upper-duff samples did require longer watering duration periods to achieve this threshold as compared to moss. The study further notes that moss was influenced by afternoon weather trends, while bulk density and feather moss species affected fuel moisture changes. Research limitations are also disclosed to improve future testing and provide context for the results of this research.

In terms of values protection, reclamation of fire-prone landscapes is recommended to restore ecological resilience against wildfires. Wildfires occurring around communities could be proactively managed using thinning, pruning, sprinkler-watering, and prescribed fire fuel treatments. In the WUI, property owners must take responsibility for areas in close proximity to their property. In this capacity, an independent sprinkler system is recommended to suppress spot fire propagation, reduce radiant heat and inhibit flame impingement around values. For broader community-based protection initiatives, a sprinkler system provides a containment line for ground ignition operations if trained personnel are available. Therefore, the utilization of sprinklers for protection against wildfires is growing, and its continued evolution can help to overcome many challenges facing wildfire management in the 21st-century.

Sprinkler-watering Distribution

The need for sprinkler-watering treatment efficacy trials became apparent in a pilot project completed during the summer of 2012 in Fort Nelson, British Columbia. While walking to the sprinkler plot the surface transitioned from a crunchy sensation to a softer feeling beneath my feet as the forest floor changed from dry to wet. At this particular upland boreal forest site, the fuel moisture changes achieved by sprinkler-watering were visible because hydrated fuels turned a darker colour within the 10 m sprinkler radius (Figure 29). Similarly, gaps in sprinkler-watering coverage were caused by vegetation interfering with the sprinkler's spray, which was apparent when comparing the watering distribution of lowland boreal forest sites with the sprinkler control site in this experiment. When using multiple sprinklers together, partially overlap their coverage to avoid possible gaps in containment that could permit wildfire spread.

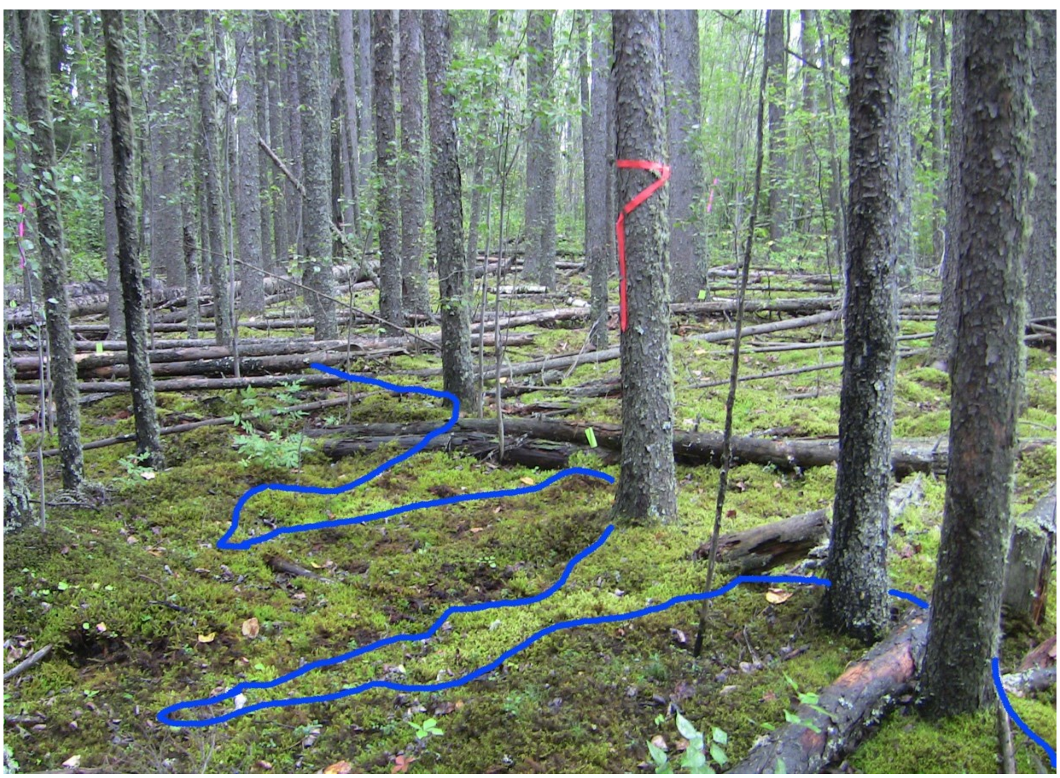


Figure 29. Visible change in moisture content from a sprinkler treatment, illustrating the difference in fuel moisture achieved. Spray coverage is delineated by blue line and the darker coloured left side represents sprinkler-watering areas.

As expected, equivalent rainfall values decreased for sample locations that were further away from the sprinkler, because there is a greater probability of vegetation obstructing the sprinkler spray. Sprinkler water distribution for lowland boreal forests samples was more variable than the sprinkler control site, when vegetation was removed; a new sample distribution plot became evident. More specifically, sprinkler-watering treatments exhibited a wave pattern at the sprinkler control site that can be separated into 4 distribution zones listed below:

Sprinkler Impact (0 to 3 m)
Secondary Arc (3 to 7 m)
Primary Arc (7 to 10 m)
Water Drift (10 to 12 m)

An impacting sprinkler has an arm that periodically contacts the sprinkler spray to distribute the water coverage. When the impacting arm collides with the water spray, it soaks an area roughly 3 metres in diameter around the sprinkler, meanwhile the temporarily deflected sprinkler spray forms a shorter secondary sprinkler arc between 3 to 7 metres in length. When the spray is not obstructed by the impacting arm the primary sprinkler arc covers 7 to 10 metres away from the sprinkler, and at the furthest end of the primary arc is the water drift zone that is affected by ambient winds. Wind also affects distribution of the primary and secondary sprinkler arc by forming larger peaks and troughs in the wave pattern. As well, it is reasonable to expect that water zones would have different water droplet sizes, which might affect absorption. Overall, mean sprinkler-watering distribution rates achieved in this experiment were 10 mm of equivalent rainfall per 3.8 L of gas, which took approximately 3 hours and 13 minutes to expel 3,142 L of water over each treatment plot. This watering consumption would be considered relatively low compared to other fire suppression tactics currently in practice, and it is possible to store a water supply. It is important to note, results from this study only apply to the sprinkler system described in this experiment.

Sprinkler-watering treatment can be modified for localized settings using features that customize water distribution. Figure 30 shows a brass deluxe impact sprinkler on hose-end spike base comes with several additional features. For example, in the model shown a distance control flap can be lowered to limit sprinkler spray up to half its radius; likewise, the diffuser screw can be set to obstruct sprinkler spray, producing a mist while shortening spray distance up to 25%. If the trip pin is down, the arc adjuster restricts the coverage between 20^{o} to 360^{o} depending upon the user's setting, otherwise the sprinkler will rotate 360^{o} clockwise (Rain Bird 2010a). These sprinkler features were not used in this research to maintain a broad inference space and to standardize treatment, but are recommended to customize spray pattern around specific values or areas.

Sprinkler Features

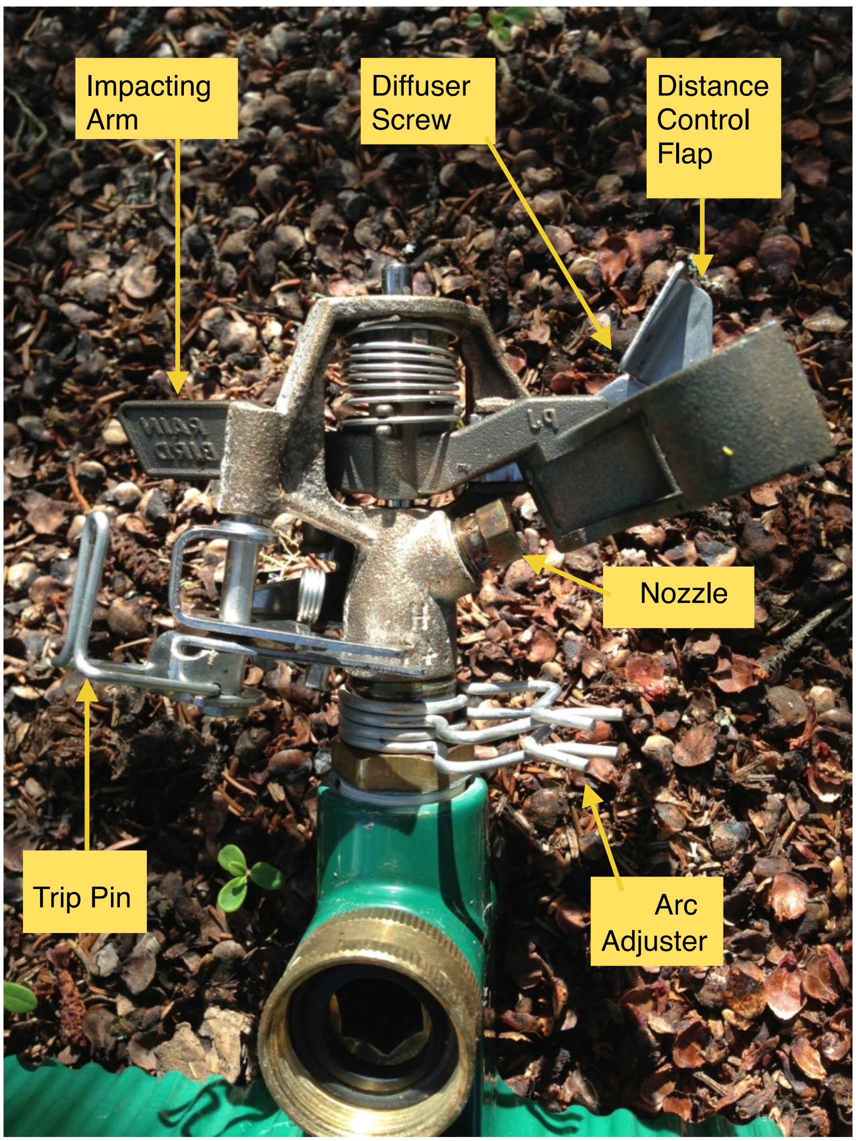


Figure 30. Rain Bird brass deluxe impact sprinkler on hose-end spike features.

Fuel Hazard Reduction

The results of this experiment indicate that sprinkler-watering mitigated moisture loss between repeated measures. Indeed, a relatively small amount of water resulted in a considerable increase of moss moisture content. This study found the water use efficiency (WUE) levels for moss and upper-duff moisture change was 1 mm and 5 mm of equivalent rainfall. The sprinkler-watering curve can help fire managers decide how much water to apply when the availability of water, gas, and equipment may be constrained. Gravimetric fuel moisture changes indicated that the majority of feather moss samples achieved values beyond their ignition probability; however, several of its control samples remained flammable. Importantly, feather moss absorbed the majority of sprinkler-watering applied, thereby limiting access to upper-duff moisture changes. This sheltering effect of the feather moss on upper-duff samples likely represents the explanation for the positive skew in watering samples observed in Figure 23. Despite this dynamic, a transformation was able to smooth upper-duff moisture changes enough for ANOVA testing, even if this data manipulation technique is less than ideal. A greater sprinkler-watering intensity might overcome any potential moss sheltering effects to increase infiltration. Additionally, operating sprinklers at night and during cooler temperatures enhances water absorption.

At the beginning of this study, it was hypothesized that increased sprinkler-watering would result in continual improvement in moisture changes, but the sprinkler-watering curve demonstrates a nonlinear relationship. At least 10 mm and 20 mm of equivalent, rainfall is recommended to change feather moss and upper-duff moisture content levels respectively to reduce fuel hazard beyond ignition. More generally, the relationship between sprinkler-watering and gravimetric moisture change is the inverse relationship observed between drying fuels and their associated fire behavior. Table 11 summarizes the sprinkler-watering treatment levels utilized in this study, and their changes in the fuel moisture codes observed; the highlighted rows indicate recommended sprinkler-watering treatment for feather moss and upper-duff organic sample containers.

Table 11. Sprinkler-watering treatment levels; recommended feather moss (green) and upper-duff (brown) sprinkler-watering treatment levels are highlighted.

Sprinkler-watering Treatments

Treatment Level	Sprinkler Watering			Feather Moss			Uppper Duff		
	Gas (L)	Equivalent Rainfall (mm)	Water (L) Consumed*	FFMC Before**	Moisture Changes***	FFMC After**	DMC Before**	Moisture Changes***	DMC After**
1	0.0	0.0	0	67	-15%	78	44	-12%	50
2	1.9	6.9	2,168	86	188%	8	51	31%	38
3	3.8	10.0	3,142	68	140%	13	58	39%	39
4	4.2	12.5	3,927	47	243%	0	44	73%	20
5	7.6	21.2	6,660	75	280%	0	45	84%	18
6	11.4	28.0	8,796	73	209%	2	67	72%	33
7	15.1	35.0	10,996	51	417%	0	13	115%	0
8	17.0	32.4	10,179	69	356%	0	48	120%	12

* Plot 10 m radius multiplied by equivalent rainfall.

** Conversion of mean moss and upper duff fuel moisture into fuel moisture codes FFMC and DMC (Equation 9 and 10).

*** Mean moisture changes between before and after measures.

Fuel Trends

The afternoon weather patterns caused moss moisture values to change throughout each day (Van Wagner 1977). For example, solar radiation drives evapotranspiration, which is associated with increasing temperatures causing moisture retention to be adversely affected. Moss's time set p-value 0.053 reinforces that temporal grouping of samples likely improved accuracy of the results. The moisture changes observed in the moss control site remained relatively stable between repeated measures, whereas the corresponding sprinkler-watering samples showed a pattern of declining moisture through the day (Figure 27). Generally, sprinkler-watering moisture changes varied throughout the day for moss, and when time set means were examined over multiple days, upper-duff drying trends became evident (Figure 28). More specifically, sprinkler-watering treatments below 21 mm of equivalent rainfall could be insufficient to change upper-duff moisture values beyond their ignition threshold. Based on these results, sprinkler-watering should focus on surface fuel to prevent spot fires, and hydration of upper-duff to prolong moisture retention and defend against high-intensity wildfires that could preheat and dry fuels.

The moisture changes observed in moss and upper-duff samples were also influenced by bulk density, samples that had a lower bulk density tended to have a greater moisture change. This was surprising because it was assumed that moisture content increases with bulk density; however, in this study a lower bulk density absorbed more moisture. These results can be misleading because the moisture changes were expressed as a percentage of the oven-dried weight; therefore, the amount of water absorbed is relative to the dried organic weight.

Feather moss species might be helpful for identifying fuel moisture regimes. Based on observations conducted, red-stemmed and stair-step feather moss seem to prefer different sites. The soil characteristics might be related to red-stemmed and stair-step feather moss anatomical structure discussed in methods. Difference between species may seem miniscule; however, their cumulative effect could be important to identifying when planning a sprinkler-watering location.

Research Limitations

Planning and implementing a robust field experiment represents a difficult task because unforeseen circumstances cause decisions that have far-reaching implications for experimental design. In this experiment, sources of error were either generated during sampling or related to experiment design flaws. Below is a list of the most significant sampling and design errors experienced in this study including a brief discussion about their possible impact on the results collected:

Sampling Errors

1. A primary concern was loss of organic matter during sampling. To avoid organic material loss, samples were handled with care. Since organic samples were relatively intact most of the debris was not lost, it is estimated that losses represent a small fraction of the overall volume.
2. Cutting organic material from the forest floor disturbs soil structure. Severing the roots could theoretically stress live fuels, or the watering treatment could alternatively stimulate new growth. These unintended cumulative effects might influence results, especially after multiple days.

3. Consistency between repeated measures' sample time was not always exact during testing, which may have influenced moss moisture response in samples given the diurnal gradient. Sampling was always completed during the afternoon hours, due to unforeseen circumstances there were some difficulties in replicating the exact timing of repeated measures.

Design Errors

1. Repeated malfunctioning of the tripod sprinkler base created a lot of wasted time and effort, and if sprinklers were more thoroughly tested prior to field sampling this problem could have been identified and avoided.
2. Sample containers were constructed with plastic to prevent them from absorbing or releasing moisture during sampling. Condensation formed on the plastic containers leaving freestanding moisture, thereby creating a higher moisture content bias. This error would be equal among samples, but it is unknown if the effect is significant relative to the container volume.
3. Field weighing of samples was done on the forest floor, which has a soft surface. Placing a hard surface below the scale might improve scale accuracy, which could be easily changed for future replications.

The above sampling and design errors provide context about how the experiment was conducted. Careful planning reduces the likelihood of impromptu decision-making that can have experimental implications, nevertheless, there will always be unexpected challenges when working in the field environment. Lastly, a match ignition test during the sampling process would indicate surface fuel flammability.

FireSmart Zonation

The primary concerns of most fire management organizations is wildfire risk (Hardy 2005), and more importantly how to minimize it with a tactical response. Every season, new strategies and tactics are integrated into wildfire prevention in order to mitigate and overcome the many challenges wildfire management faces in the 21st-century. Unlike previous or current fire suppression strategies that rely on direct attack, a fire prevention strategy relies on indirect attack to mitigate fire danger. FireSmart zones for wildfire management planning are shown in Figure 31, these zones could be coupled with sprinkler programs (Partners in Protection 2003).

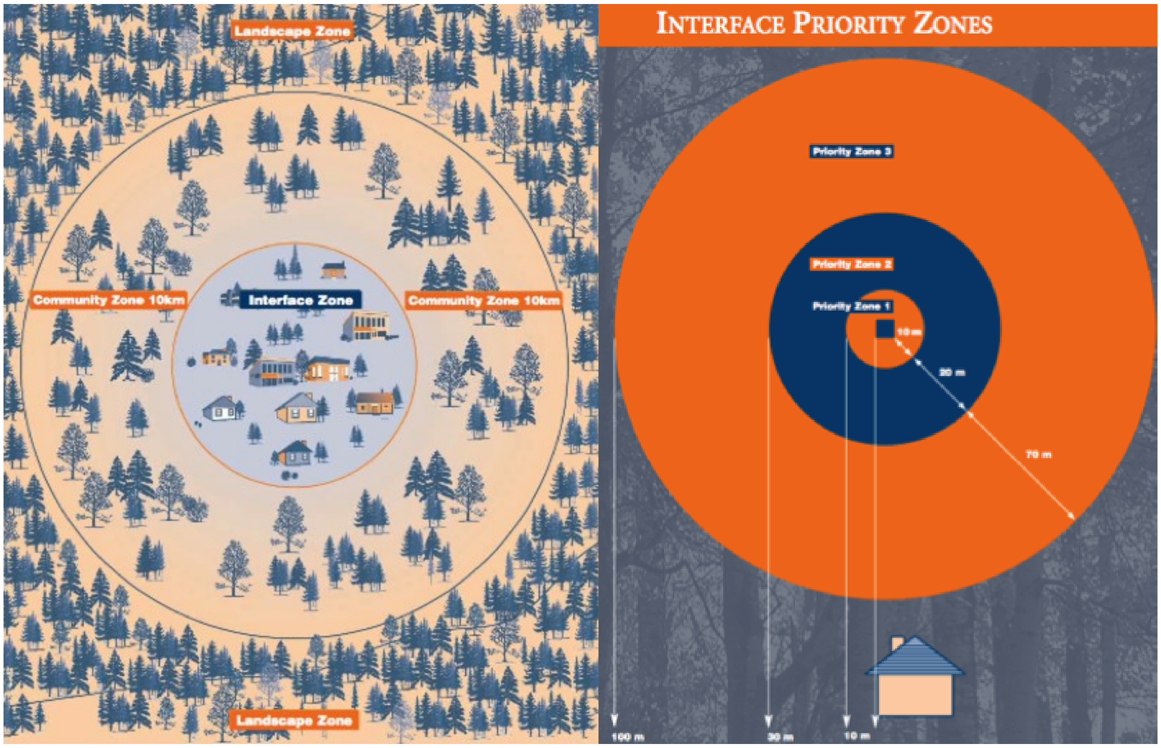


Figure 31. FireSmart zones with interface priorities (Partners in Protection 2003).

Landscape Zone (Outside of Community Zone)

Currently, many established wildland fire agencies are responsible for managing the landscape zones in North America. These efforts are carried out in order to manage public resources and minimize wildfire risk. Often the landscape zone is managed in tandem with resource activities that may include controlled burning to reduce post-harvest fire risk and mitigate fire danger. Fire Management Plans (FMP) are landscape documents that identify fuel values and use them as a basis for emergency response plans that coordinates wildfire tactics to achieve a desired outcome. Territorial fire management agencies should relinquish their wildland urban interface responsibilities and embrace land management as their primary mandate.

Community Zone (10 km around the Community)

The community zone represents a 10 km buffer between the landscape and interface zones. Municipalities should be responsible for controlling wildfires around communities, and a Community Wildfire Protection Program (CWPP) can explain the tactics needed for probable fire situations based upon the specific environment (Parisien 2011). A CWPP should identify decision points in order to implement a defensive plan for approaching wildfires, and include hazard reduction treatments to mitigate ignition probability and wildfire intensity (SAF 2004). This would require training of fire departments and other first responder personnel. If a sprinkler-watering containment line were previously established, prescribed fire operations could burn fuels to prepare for approaching wildfires.

Community zones are managed through fuel prescription written for the CWPP. Fuel prescriptions alter forest structure through vegetation conversion, organic matter reduction, fuel isolation and removal (Partners in Protection 2003). Snider (2006) compares fuel reduction and fire suppression programs to show that fuel management initiatives are justified. Figure 32 depicts two popular fuel treatments that help to prevent crown fires and spot fires from spreading in forests: thinning and pruning. Thinning a stand of trees reduces the chances of a continuous crown fire by removing the crown connectivity by lowering stocking density (Schroeder 2006). It is designed to emulate low-intensity wildfires by removing juvenile and decadent trees; however, Jandt *et al.* (2005) note that drier fuel moisture values in thinned stands could increase fire intensity. Pruning is meant to emulate a surface fire's scorch height and its best suited for mature trees that can withstand a surface fire. Pruning treatment removes susceptible ladder fuels to prevent tree torching, which casts embers that can create spot fires. However, it also can create increased understory wind infiltration, which could potentially dry fuels and help to spread a wildfire (Van Wagtendonk 2006). Fuel hazard treatments are foster resilient ecosystems, and sprinkler-watering treatment can be integrated into this approach to satisfy both goals.

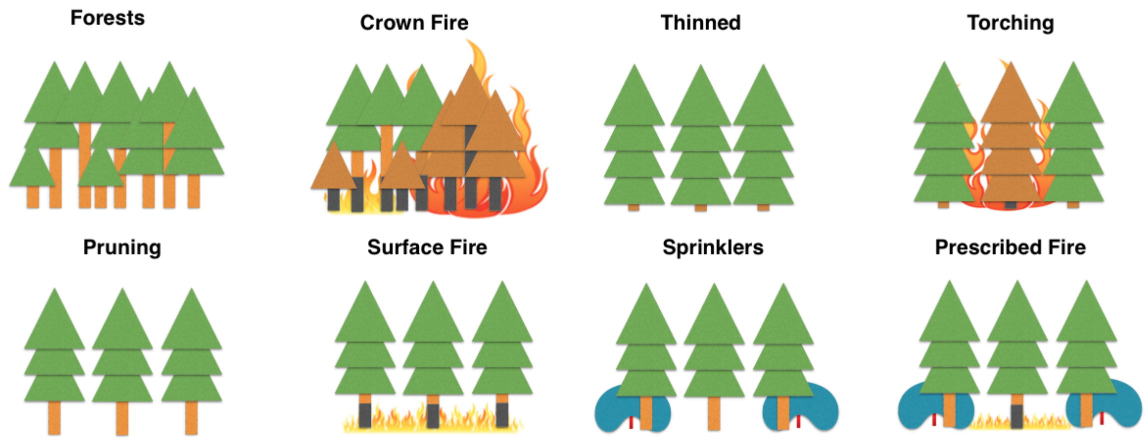


Figure 32. Fuel treatments: unmanaged forest, thinning, pruning, and sprinklers.

Combining a fuel treatment with a sprinkler system could improve its effectiveness in containing wildfires at predetermined control points. Removal of vegetation would improve sprinkler-watering distribution in fuel treatment areas, and the sprinkler system itself would create a wetter microclimate to counteract fuel drying and control fire growth. Watering hazardous fuels to reduce the fire hazard around values would provide protection; however, increased sunlight and moisture would likely encourage vegetation growth. If necessary, these fuels could be controlled through routine burning prescriptions that would provide training opportunities for first responders to prepare for unplanned wildfire situations that may require ignition of the community zone for greater protection.

Interface Zonation

A landowner should be responsible for maintaining appropriate standards of care when living in fire-prone ecosystems. Homes that are improperly protected may burn and transfer embers to adjacent values. FireSmart's interface zone (Figure 31) is subdivided into three priority zones for landowner protection.

Priority Zone One (10 m from value):

A 10 m defensible space buffers a value from radiant heat and provides a relatively safe environment for first responders to operate. Property owners should be responsible for their defensible space (Johnson *et al*. 2008) with building codes that include Structure and Site Hazard Assessment Forms (Partners in Protection 2003). When completing a structure assessment, photos should be taken of surrounding fuel, structural deficiencies, and values needing protection. Landowners should be advised on costs regarding fire protection in order to encourage its prevention, if a landowner has not properly prepared for wildfire, and then wildfire management agencies should act to recover their costs. Ultimately, the ability of wildfire management agencies to protect private assets during wildfires will correspond to human life then public infrastructure risks, and owners should be aware of this when making decisions about wildfire protection.

Priority Zone Two (10 to 30 m from value):

At priority zone one's boundary, a sprinkler perimeter could be set up to hydrate fuels and defend against spot fires. This perimeter would create a 20 m buffer around the value from the approaching wildfire, and it is important not to spray structures because this could cause water damage. When setting up the sprinkler system protect the hose from burning because a leak may cause a reduction in water pressure, which could lead to sprinkler failure (Walkinshaw and Ault 2009b). In order to prevent this from happening, a weeping hose can be used or lined hoses can be buried in mineral soil to protect them from burning. For intense wildfires, fortifying an area by adding a second sprinkler line can be coupled with ignition operations to burn fuels ahead of the wildfire (Fogarty 1996). In the event of evacuation, it is imperative that safe access to the sprinkler system's water pump is provided for first responders, staff will activate the sprinkler systems as the wildfire approaches. Once the area is safe to enter, responders may return to extinguish fires that could cause damage if left alone.

One important factor to keep in mind when implementing sprinkler protection tactics is that availability of water during drought situations could constrain sprinkler operations, thus switching the focus from fuel saturation to water use efficiency. In water-limited environments, sprinkler operations could focus on water distribution rather than fuel moisture changes. These environments tend to be dominated by surface fuels rather than deep organic soils making fuel saturation harder to maintain. In drought situations, sprinkler-watering can be a controversial issue, to prepare for an issue an emergency catchment could store water needed for the sprinklers. As well, a foam induction system can further conserve water and prolong protection (Ault 2009). In some situations, sprinkler systems are more effective than a water nozzle, and sprinkler can conserve water use because they control water distribution. Nevertheless, this experiment occurred in lowland boreal forests where water is easy to find.

Priority Zone Three (30 m from value):

For Priority Zone 3, the sprinkler protection area can be widened using prescribe burn operations. A burn plan should identify conditions to contain a wildfire at the most advantageous points and ground ignition timings and patterns designed to control a fire's intensity and spread direction. By helping to meet these defined objectives, sprinkler-watering can be an effective tool in preventing surface fires with less than 2,000 kW/m intensities. Indeed, a video recorded by FPInnovations Wildfire Operations shows the sprinklers stopping the spread of a vigorous surface fire (Large 2010). This research suggests that at least 3.8 L of gas is required per day to modify feather moss moisture beyond ignition values, and more than 7.6 liters of gas is recommended to ensure that upper-duff moisture content is enough to prevent ignition during high-intensity wildfires. This is particularly important because higher intensity fires can preheat fuel and make sprinkler-watering ineffective. Therefore, sprinkler tactics could be coupled with ground ignition operations to ensure lower intensity fires do occur around sprinklers, and these operations should be coordinated within the CWPP.

Sprinkler Innovation

Emerging demand for sprinkler operations in wildfire management is becoming a catalyst for sprinkler innovation. In 1971, Quintilio *et al*. speculated increasing the role of sprinklers in wildfire suppression scenarios due to the "Conservation of water and manpower, simplicity, portability, and low cost suggest a potential use on operational prescribed burns and wildfires". It is important to think about sprinklers beyond their typical structure protection niche in operations, as this will allow wildfire management programs to discover new efficiencies in wildfire duties. For example, sprinklers can be used to help mitigate hazardous areas, reinforcement of fireguards, mop-up difficulties, and overall fire severity reduction. There are many potential applications of sprinkler-watering treatments in wildfire suppression, and widespread adoption of sprinkler protection programs will generate linkages for further innovation. This marks an important change in fire management strategy and tactics (ESRD 2014), and this transition will require sprinkler protection and prescribed fire skills in the future.

Innovation in sprinkler technology for wildfire management presents an entrepreneurial opportunity for manufacturers, and increased consultation with sprinkler providers would likely lead to synergies including automation for irrigation (Rain Bird 2013, Rain Bird 2014b). For example, a sprinkler tractor shown in Figure 33 is propelled by water pressure and this design could be scaled to negate the need for firefighters when burning flashy fuels that spread rapidly and are known to cause entrapment. As well, operational research could be a great source of information, for example, cases studies could document sprinkler operations to improve protection programs. If wildfire organizations want to develop sprinkler protection programs effectively, further exploring the potential outcome of these kinds of sprinkler synergies could prove beneficial.

Figure 33. A water-propelled sprinkler tractor that follows the hose.

4 CONCLUSION

An unfortunate reality of human behaviour is that bad things usually happen before people summon the will to change. We are a reactive society and this thesis was written in response to the “Slave Lake” 2011 Flat Top Complex wildfire (ESRD 2012) that had tragic consequences. It is important to note, that 23 other communities in the province were threated during that time and a similar fate or worse could have happened to multiple communities. A changing fire regime is increasing wildfire activity (Weber and Flannigan 1997), while fire exclusion policies continue to extinguish wildfires, potentially causing more intense wildfires. This creates catastrophic wildfire situations that place people and their property in imminent danger. Meanwhile, development in and around North America’s forests continues to add values to already fire-prone ecosystems with little thought to wildfire prevention. Wildfire agencies are faced with insufficient resources to meet the burgeoning demand of current wildfires. These pressures are expected to become drivers for change in strategies and tactics.

The fire exclusion paradox suggests wildfires that we suppress today often become the foundation for fires that we may fight again in the future. A fire exclusion strategy is a self-defeating process that undermines the necessity of wildfires as a natural feedback mechanism for forest renewal. A fire prevention strategy that recognizes both environmental and economic obligations represents a viable solution to this problem, and shifting from a reactive fire suppression strategy to a proactive fire prevention strategy (WMB 2010) is central to this claim. Explicitly, sprinkler prevention programs are cost-effective because they enhance response capacity through proactive planning as opposed to a reactive response. The fire prevention strategy outlined in Figure 34 is safer than a fire suppression strategy because it mitigates fire danger through indirect attack tactics, while there is time still available to respond, and ultimately reducing the risk to both first responder personnel and surrounding communities.

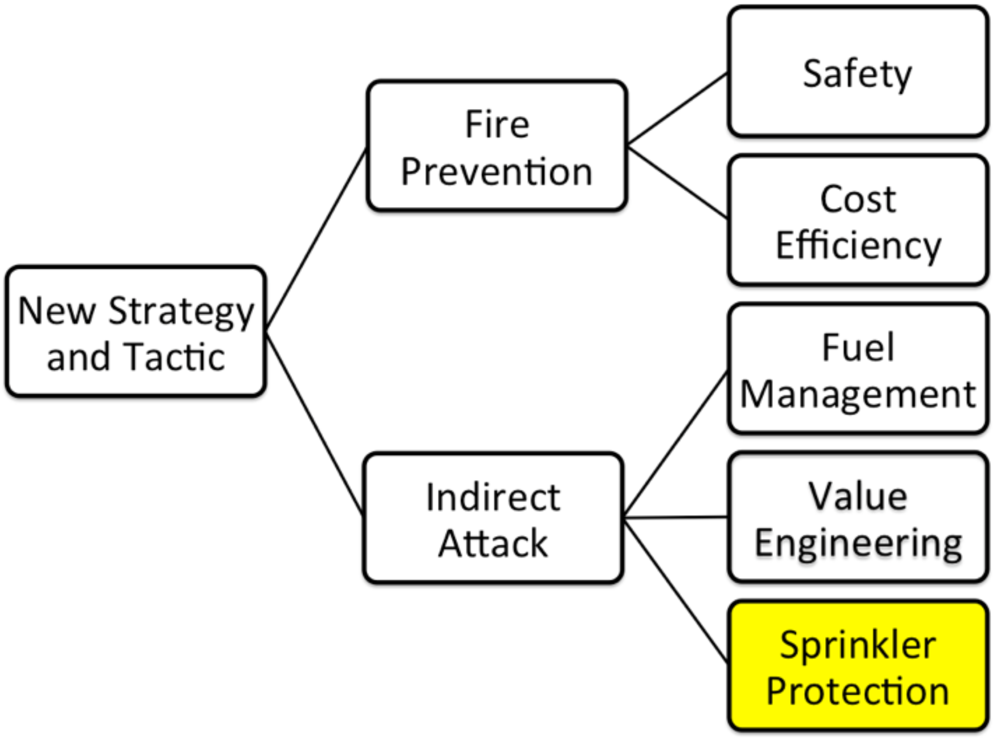


Figure 34. A recommended fire prevention strategy that uses indirect attack to manage wildfires; sprinkler protection is highlighted as the focus of this research.

Indirect wildfire tactics such as fuel management, value engineering, and sprinkler systems reduce wildfire response efforts. Sprinkler-watering efficacy was the focus of this thesis, which found that sprinkler-watering treatments were effective at changing feather moss and upper-duff samples moisture content. Sprinkler-watering distribution was examined in lowland boreal forests and a sprinkler control site; the mean sprinkler-watering distribution was approximately 10 mm of equivalent rainfall per 3.8 L of gas. Sprinkler-watering treatments displayed a diminishing return in water use efficiency as fuels approached saturation. The sprinkler-watering curve shows 10 mm of equivalent rainfall will change feather moss moisture to near saturation levels, whereas it is recommended that upper-duff have 20 mm of equivalent rainfall to change moisture content to begin inhibiting combustion. It is believed that sprinkler-watering can modify moisture content to be within suppression limits of control.

Sprinkler protection programs are a necessity for emerging fire regimes. A long-term fire protection strategy requires cumulative burning around values to maintain a healthy pyrogenic ecosystem. Fire exclusion policies have led to a stagnation and decline in forest health, making them more susceptible to wildfires. A fire prevention strategy that focuses on the underlying relationship between humans and wildfires will improve the current situation and help to overcome the many challenges inherent to wildfire management in the 21st Century. Wildland fire is a natural disturbance that is necessary for forest renewal, and management agencies have an obligation to sustain the environmental benefits to maintain natural resilience. By embracing preemptive efforts to contain wildfires, the demand on wildfire protection programs overall decreases, enhancing the safety of firefighting personnel and the surrounding communities, sprinkler protection programs can play a pivotal role in this process.

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6 APPENDICES

A.1 Materials

Table 12. Quantity of items required to conduct the sprinkler research

Quantity	Item	Quantity	Item
1	Communication Device	2	Mark 3 Suction Hose
1	GPS	12	Wye Valves (1.5”)
1	First Aid Kit	2	Fuel Containers
2	Emergency Response Plan	8	Hose Reducer (1.5” to 3/4”)
1	Wire Cutters	8	Wye Valves (3/4”)
1	Fencing Wire	8	Sprinklers
1	Drill with Bit (1/8”)	8	Pressure Regulators (345 kPa)
1	Exacto Knife		
1	Measuring Tape	1	Water Pressure Gauge
1	Permanent Marker	1	RAWS
200 ft^2	Hardware Cloth (6 mm)	1	Electronic Scale (0.1 gram)
1	Bread Knife	1	Writing Pencil & Datasheet
1	Plastic Placemat	1	Forestry DME
1	Fabric Scissors	1	Parabolic Densiometer
48	Moss Containers	1	Ruler (1 metre)
48	Duff Containers	1	Nylon Rope (11 metres)
96	Water Containers	1	Diameter Measuring Tape
48	Flag Markers	96	Freezer Bags (3.8 L)
1	Compass	3	Large Plastic Containers
12	100’ Fire Hose (1.5")	2	Fuel Drying Oven
2	Mark 3 Water Pump	60	Nalgene Cylinders
2	Mark 3 Accessory Kit	1	Hardware Cloth (2 mm)
		1	Hardware Cloth (15 mm)

Keeping an inventory sheet will provide a checklist for the experiment equipment.

A.2 Datasheets

Copies of the site setup datasheet, sampling datasheet, and covariate datasheet.

Site Setup

Date: **Observer:**

Research Site:

Location				Container Number				Tare Weight			
Treatment	**Time Set**	**Plot**	**Sample**	**Moss**	**Duff**	**Water 1**	**Water 2**	**Moss**	**Duff**	**Water 1**	**Water 2**
	A		1								
	A		2								
	A		3								
	A		4								
	A		5								
	A		6								
	A		7								
	A		8								
	A		9								
	A		10								
	A		11								
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	D		44								
	D		45								
	D		46								
	D		47								
	D		48								

Notes:

Sampling

Date: **Observer:**

Research Site:

Sample Location	Day 1					Day 2					Oven Dried	
	Moss (g)	Duff (g)	Water 1 (g)	Water 2 (g)	Time	Moss (g)	Duff (g)	Water 1 (g)	Water 2 (g)	Time	Moss (g)	Duff (g)
1												
2												
3												
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Covariates

Date: **Observer:**

Research Site: **Average tree height:**

Sample	Closure (%)	Moss (Spp.)	Tree Distance (m^2)	Tree (Spp.)	Tree Diameter (cm)	Sample Distance (cm)
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