Assessment of the Impacts of Prescribed Fires on Soil Quality and Cultural Impacts of Interdisciplinary Collaboration

A Dissertation
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Authorization to Submit Dissertation

This dissertation of Scott J. Fennema, submitted for the degree of Doctor of Philosophy with a Major in Water Resources - Engineering and Science Option and titled "Assessment of the impacts of Prescribed Fires on Soil Quality and Cultural Impacts of Interdisciplinary Collaboration," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Dedication

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Vindicate me, O Lord, for I have walked in my integrity, and I have trusted in the Lord without wavering. Prove me, O Lord, and try me; test my heart and my mind. For your steadfast love is before my eyes, and I walk in your faithfulness.

Psalm 26:1-3 (ESV)

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Statement of Contribution

Chapter 4: Integrating Cultural Perspectives into International Interdisciplinary Work was co-authored by Dr. Karen Trebitz and Dr. Keegan Hicks. In this chapter, Karen and I developed the literature review conjunctively. Karen developed, conducted, and coded the survey and interview data; Karen and I completed the data analysis and derived the results. I led the development of the interdisciplinary framework and the additions of intercultural discussion into the interdisciplinary framework. Keegan served as a technical review and provided valuable insight.

Chapter 1: Introduction

Wildfires in the Western US have been increasing at alarming rates, especially in the last 40 years (Westerling et al., 2006). The increase in wildfires over the last ten years and the imminent threat of wildfires will have devastating economic and ecologic consequences. According to the National Interagency Fire Center, more than 9 million acres of land burned in 2015 alone. The total number of burned acres has exceeded 9 million acres 4 times since 1960—three of which have occurred in the last eight years (2007, 2012, 2015). Recent fire risk modeling indicates the number of weeks classified as high risk of extensive wildfires will increase by 600% in parts of the western US (Barbero et al., 2015). Under the stress of climate change, tree mortality is predicted to increase (Allen et al., 2010) and lead to more intense and larger fires (Barbero et al., 2015). In some regions, increased rates and intensities of forest fires are already taking place (Gillett et al., 2004; Stocks et al., 1998; Westerling et al., 2006). As climate change intensifies, fire regimes will intensify (Flannigan et al., 2000).

Forests have been managed such that wildfires have been “deprived of 10 or more natural fire cycles” (Brown et al., 2004). Post-wildfire, scarred landscapes can be highly unstable, resulting in heavy sediment and nutrient transport to downstream water bodies for many years following the fire (Tiedemann et al., 1979; Moody & Martin, 2001; Neary, Ryan, & DeBano, 2005). Forest managers apply various techniques to manage risk from no action (which does not reduce the risk of wildfire), to mechanical forest thinning (Agee and Skinner, 2005; Graham et al., 1999; Miller et al., 2020), prescribed burning (Agee and Skinner, 2005; Covington and Sackett, 1984; Graham et al., 1999) to clear-cutting forest stands (Bergeron et al., 2002).

Forest managers use a range of techniques to reduce fuel loads through prescribed burns. Broadcast burning is a dispersed method of burning used to reduce ground cover and ladder fuels (Busse et al., 2014). Broadcast burns typically result in low severity burns impacts (Thies et al., 2005). Slash pile or hand pile burning concentrates the impacts of burning, sterilizes the soil beneath the piles (Korb et al., 2004), and has been found to impact forest landscapes for more than 5 decades (Rhoades and Fornwalt, 2015).

In addition to choosing a method, forest managers must pick a season when to apply prescribed burns. Managers must have the available resources, such as experienced staff and funding, and appropriate weather conditions to consider applying prescribed burns (Miller et al., 2020). Managers must also consider the risks associated with burning during different times of the year. For example, summer through late fall to early winter is considered the wildfire season. If a prescribed burn gets out of control in the fall time, winter will help put that fire out. If a prescribed burn gets out of control during the springtime, it could lead to longer and potentially larger fire (personal communication with Kendra Fallon, US Bureau of Reclamation Fire Coordinator). Managers must also consider ecosystem impacts when determining the timing of prescribed burns. However, previous research have shown conflicting results. Swezy and Agee (1991) found that ponderosa mortality is higher when prescribed burns were done in the spring whereas Thies et al. (2005) found increased mortality when burns were done in the fall.

Wildfires affect forest soils by removing large quantities of organic matter, decreasing porosity and infiltration, and increasing erosion (Benavides-Solorio and Macdonald, 2001; Certini, 2005; Martin and Moody, 2001; Meyer and Pierce, 2003). Severe fires also cause soil hydrophobicity (Debano, 2000; Huffman et al., 2001; Robichaud, 2000), which further decreases infiltration (Burch et al., 1989; Certini, 2005a; Pierson et al., 2008; Robichaud, 2000) and increases erosion rates (Benavides-Solorio and Macdonald, 2001; Keeley, 2009; Meyer and Pierce, 2003). In small plots in the Colorado Front Range, erosion rates increased by 10 to 26 times following a severe wildfire (Benavides-Solorio and Macdonald, 2001). Within the Pacific Northwest, post-fire erosion debris slides are predicted to increase (Wondzell and King, 2003).

Forest management practices can also lead to changes in hydrologic response such as increased peak streamflow (Bowling et al., 2000; Jones and Grant, 1996; Stednick, 1996), earlier runoff, and snowmelt (Bowling et al., 2000; Storck and Bolton, 1999), and increased flood frequency (Alila et al., 2009). However, these forest disturbances (whether for fire risk reduction or timber harvesting) often increase erosion (Edeso et al., 1999; Karwan et al., 2007; Miller et al., 1988; Patric, 1976). In a paired watershed study, Miller et al. (1988) collected water samples below a clear cut, a thinned, and a control watershed on a 15 to 60-minute basis for three years. Miller found that sediment yields were 20 times and three times larger for the clear cut and thinned watersheds, respectively, than the control. Since the eroded soils are often rich in organic and inorganic phosphorus, increased erosion results in increased phosphorus (P) loading to downstream water bodies.

Natural resource managers focus much on reducing non-point source (NPS) P loading to protect water bodies and drinking water supplies from harmful algae blooms. Management is typically focused on urban (Soil Conservation Service 1992; Novotny 1995) and agriculture sources (Bergman, 2011; Daniel et al., 1994; Kleinman et al., 2011; Sharpley et al., 1994; Sims et al., 1998) but overall P management in forests headwater systems has mostly been ignored. NPS P loading is costly and challenging to measure (Carpenter et al., 1998; Sharpley et al., 2002).

P is often discussed in the literature in terms of its form (e.g., dissolved or particulate; Rittenburg et al., 2015), species (e.g., orthophosphorus; Miller et al., 2008), or mineralization state (e.g., inorganic, or organic; Heron et al. 2021). Total P (TP) describes the entire amount of dissolve and particulate P present. Dissolved and soluble P forms are bioavailable, referred to as water extractable P (WEP) in this dissertation, are key to understanding for the protection of landscapes (Fang et al. 2002).

Movement of P can occur through dissolution in water and physical processes, such as erosion (Haygarth and Jarvis, 1999; Haygarth and Sharpley, 2000; Thompson et al., 2005). Particulate P is typically bound to clay particles and is transported through erosion (Scholz, 2010; Thompson et al., 2005). Dissolved P (DP) can be transferred by leaching and can move through multiple hydrologic flow paths such as deep groundwater infiltration, lateral flow, or saturation excess runoff (Haygarth and Sharpley, 2000). However, DP is highly reactive and typically binds to soil quickly. Transfer of P occurs between WEP and particulate P phases based upon equilibrium dynamics (Froelich, 1988; Smith et al., 2005). The P transport pathways occur at multiple spatial and temporal scales (Haygarth and Sharpley, 2000; Rittenburg et al., 2015). Increased erosion rates following fires are often the primary concern for phosphorus as up to 95% of P is transported bound to sediment (Meybeck, 1982). Particulate P within waterways increases directly with sediment (Carpenter et al., 1998; Puustinen et al., 2007; Uusitalo et al., 2000). However, less is known about the impacts of fire on WEP and TP.

Many alpine lakes surrounded by forest are critically limited by P availability (Schindler, 1977). If the P availability were to increase in the correct form, these P limited systems would see increase in primary productivity, such as algae blooms, that can lead to eutrophication (Wood and Beckwith, 2008)—the primary cause of water quality impairment in the United States (Sharpley et al., 2003; U.S. Environmental Protection Agency, 1996). P loading affects not only the health of the water bodies (Carpenter et al., 1998; Correll, 1998) but also affects the socio-economic factors such as tourism (Imperial and Kauneckis, 2003) and real estate prices (Boyle et al., 1999; Liao et al., 2016).

Forests are complex systems requiring numerous technical experts to work collaboratively across disciplinary bounds to develop forest management plans. Working across disciplines has numerous challenges. Disciplinary language barriers disrupt communication (Cosens et al., 2011; Repko, 2012). Disciplinary methodologies vary (Repko, 2012), which can be frustrating and often culminates in a lack of trust between disciplines and research group members (Cosens et al., 2011; Eigenbrode et al., 2007; M Heemskerk et al., 2003; Newell, 2001). To overcome the difficulty working across disciplinary boundaries, there is a formalized process within the interdisciplinary research literature that aids in building understanding across technical and disciplinary differences (Cosens et al., 2011; Eigenbrode et al., 2007; M Heemskerk et al., 2003; Newell, 2001).

Forest managers are responsible for balancing ecosystems needs, wildfire risks, resource limitations, and sociopolitical perceptions of optimal forest management. They are responsible for managing the risks of fire, fuel loads, erosion, recreation, and watershed restoration daily. Additionally, forest managers must keep the sociopolitical will in mind to balance public opinion. Managing all the risks associated with forest management is a difficult task that requires thorough knowledge of their forested systems and sociopolitical forces.

While knowledge of forest systems is growing, some questions, risks, or wicked problems have yet to be researched to understand the forest's potential impacts. Forest managers then can review the scientific literature, develop a methodology to study the question at hand. If resources are available, managers then can conduct experimentation to develop and understanding the risk at hand. Forest managers then must work collaboratively with the interdisciplinary teams, often with groups that may have conflicting objectives, goals, and technical understanding to address the initial problem studied. Figure 1-1 presents a conceptual framework of how forest managers can address questions, risks, or wicked problems.

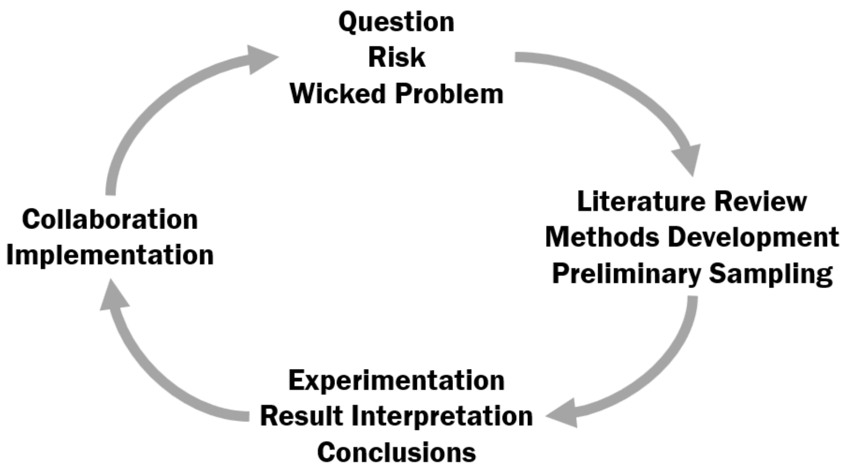

Figure 1-1: Conceptual process that forest and natural resource managers can apply to address questions, risks, or wicked problems that arise during management.

Based on the increasing risk of wildfires, the overall goal of this research was to develop a method to reproduce fire in lab setting to quantify impacts of prescribed and wildfire on forested soil, quantify shifts in forest soil P before and after fire, and expand on the current interdisciplinary methods to allow for inclusion of cultural discussion. The developed method would allow forest managers to reproduce prescribed burns or wildfires in a lab prior to understand how nutrient concentrations shift—allowing managers to allocate limited resources to the most sensitive portions of their management areas. Since the numerous parties that participate in forest management have differing cultural value and viewpoints of forest, it is critical to include discussions regarding cultural differences during the interdisciplinary forest management process. To do so, we propose an addition to the interdisciplinary process that allows for cultural discussion.

This research project was initiated in a manner similar to a forest management path. In the beginning, a question asked about how to predict P loading from a forested ecosystem. We then turned to the literature to see if previous researchers have developed predictive models regarding P loading from forest ecosystems. We completed preliminary soil sampling to try to understand soil P concentrations and distributions within the watershed of interest along the way. We noted an interesting change in soil P before and after a wildfire during the preliminary sampling, which was not well understood. We then developed a new methodology to reproduce wildfire in a laboratory setting. Chapter 2: Reproducing Wildfire in a Laboratory Setting presents a standardized, quantitative based method to reproduce wildfires on soils in a controlled environment. With the new method in hand, we then quantified fire's impact on soil P. Chapter 3: Forest Soils Response to Fire Radiative Energy Dosing quantifies the impact of fire on soil P. In my dissertation research, we never got to implement solutions to enhance forest management collaboratively. However, the last chapter of my research proposes an addition to the interdisciplinary process to include discussions about cultural differences. The addition of cultural perspectives is in Chapter 4: Integrating Cultural Perspectives into International Interdisciplinary Work.

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Chapter 2: Reproducing Wildfire in a Laboratory Setting

Abstract

Fires are known to alter a soils physical and chemical properties. It is difficult to quantify changes in the soil properties before and after fire since fire intensity is highly variable and difficult to control. Researchers have turned to laboratory methods to quantify changes in soil before and after fire. Previous research primarily has used muffled furnace to heat soils. However, muffled furnaces do not expose soils to the same conditions as fire and does not reproduce conditions found in nature following fire. Other researchers have used a variety of other methods to heat or expose soils to fire—many of which use inconsistent methods and metrics to determine experiment end points. Recent papers in the plant physiology literature have proposed a new paradigm in fire dosing experiments that requires experiments to be: 1. energy based, 2. quantitative, 3. replicable, and 4. mechanistic. This paper proposes a new energy-based method to test the effects of both wildfire and controlled burns on soils. The method applies Fire Radiative Energy (FRE) treatments to a soil collected from the Fernan Watershed in Northern Idaho. The goal of the FRE was to burn the soils to reproduce low soil severity impacts. However, FRE values that result in a low soil severity are not published. Therefore, a 2 cm soil temperature threshold of 100 °C was used as a surrogate for low soil severity burn impacts. FRE was estimated once the 2 cm soil temperature reached the 100 °C. Quantitative radiative energy measurements were taken to quantify the amount of radiative energy applied to a soil in megajoules per square meter. Low severity treatments, which replicate the impacts of controlled burns were applied to two soils at two moisture contents (field capacity and oven dried); 2 cm soil temperatures reach the threshold on 2.3 minutes on average in the dry soils and 5.3 minutes in the wet sample. The wet soils cores lost 155 grams of water following burning. The additional time needed to heat the wet soil cores was directly related to the latent heat of evaporation of water. FRE treatments ranged from 8.2 to 20.5 MJ m^{-2} and 27.4 to 42.9 MJ m^{-2} in the dry and wet samples, respectively. The proposed FRE method meets Smith et al., (2016) call for a standard method to reproduce wildfire in a laboratory setting. This new method allows land managers to quantify the impacts of wildfire or prescribed burns to soil in a lab setting.

Introduction

Wildfires in the western US increased at alarming rates, especially in the last 40 years (Westerling et al., 2006). The increase in wildfires over the last ten years and the imminent threat of wildfires will have devastating economic and ecologic consequences. Forests management has “deprived of 10 or more natural fire cycles” (Brown et al., 2004). Post-wildfire, scarred landscapes can be highly unstable, resulting in increased sediment and nutrient transport to downstream water bodies for many years following the fire (Tiedemann et al., 1979; Moody & Martin, 2001; Neary, Ryan, & DeBano, 2005). Forest management is critical to reduce risk of fire and protect downstream water quality.

Wildfires have been long known to alter soils (e.g. Debano et al., 1977; Scotter, 1970; Wright, 1976). Erosion can increase by as much as 1,000% in comparison to undisturbed forests (Elliot et al., 2006). Post-fire erosion rates are related to the removal of protective ground cover (e.g. duff layers, woody debris, vegetation) (Robichaud et al., 2013; Zituni et al., 2019), the degree of hydrophobicity (Debano, 2000; Robichaud et al., 2013; Shakesby and Doerr, 2006), and the burn severity (Doerr et al., 2006; Moody et al., 2008; Robichaud et al., 2013). Burn severity has a positive feedback on the factors that lead to increased erosion. As burn severity increases, ground cover is further reduced and more organic matter is volatilized, which coats soil particles and leads to hydrophobic conditions (Robichaud and Hungerford, 2000). Previous research suggests that hydrophobic conditions are most intense when the organic matter is heated between 175 to 205 °C and no longer exists once heated above 290 °C (Robichaud and Hungerford, 2000). Hydrophobicity decreases post-fire hydraulic conductivity (Certini, 2005; Debano, 2000; Garcia-Corona et al., 2004).

Improved forest management requires thorough understanding of how soil properties change before and after fire. However, quantifying the changes in soil properties before and after exposure to fire is difficult since fire is highly variable, and many variables, such as fire intensity, fuel loads, and burn times, cannot be controlled (Certini, 2005; Glass et al., 2008; Lombao et al., 2015; Wieting et al., 2017). Numerous researchers have turned to laboratory-based experiments to quantify the effects of fire (whether from prescribed burns or wildfire) on soils (e.g. Debano et al., 1976; Doerr and Moody, 2004; Sertsu and Sanchez, 1978; Stoof et al., 2010).

Some methodologies use a muffle furnace as a common method to heat soils (e.g. Badía et al., 2003; Krammes and DeBano, 1965; Lombao et al., 2015). Muffle furnaces are temperature-controlled chambers able to maintain constant temperatures upwards of 900 °C (Figure 2-1). In the previous experiments, researchers quantified physical and chemical changes in soils following soil heating. Typically, researchers would insert a soil into the muffle furnace for a given time with the furnace at a pre-set temperatures ranging from 100 °C (Marcos et al., 2007; Parlak, 2011; Sertsu and Sanchez, 1978; Terefe et al., 2008) to 500 or 600 °C (Debano and Krammes, 1966; Fernandez et al., 1997; Quintana et al., 2007; Sertsu and Sanchez, 1978; Terefe et al., 2008). For one particular experiment, Debano and Krammes (1966) heated hydrophobic soils up to 900 °C.

The duration of heating used in previous muffle furnace studies is variable, ranging from five minutes (Debano et al., 1976; Debano and Krammes, 1966; Doerr and Moody, 2004; Glass et al., 2008; Marcos et al., 2007) to 48 hours (Sertsu and Sanchez, 1978). Marcos et al., (2007) reported that lower temperatures and short duration treatments showed no difference in soil properties than the unheated soils.

Muffle furnace experiments provide insight to how soil changes when heated. However, numerous authors conclude that muffled furnace soil heating is unable to reproduce hydrophobic conditions that can occur following a wildfire (Badía et al., 2003; Doerr and Moody, 2004; Wieting et al., 2017). Additionally, muffle furnaces are isothermal chambers that do not allow for the direct fire contact on soils (Stoof et al., 2010; Wieting et al., 2017). From a physics perspective, a muffle furnace allows a soil to heat from all directions equally, whereas in wildfires soils are typically heated from the top down. Using a muffled furnace to document the effect of fire on soil is analogous placing a soil in a freezer to test the effects of frost heave. Haley (1952) and Kaplar (1971) conducted experiments and observed that frost heaving was only reproducible in the laboratory using top-down soil cooling experimental designs. Applying temperature changes to soil, whether heating or cooling, establishes internal hydraulic and vapor pressure gradients that alters the spatial distribution of heat, water, and stored energy. These gradients within the soils can change the distribution of soil material, soil water content, and soil nutrients.

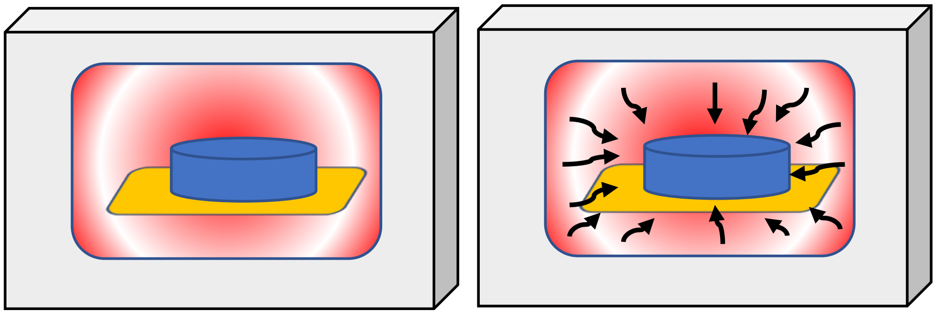

Figure 2-1: Conceptual Diagram of Soil Heating in a Muffle Furnace

Soil heating through the use of a muffle furnace does not expose soil to the same conditions as a wildfire (Stoof et al., 2010; Wieting et al., 2017). To expose soils to direct flame, Stoof et al., (2010) tested the effect of heating soils on soil water retention using two methods: a muffle furnace and a propane torch (Figure 2-2). They found that heating soil in a muffle furnace at 300 °C for at least 30 minutes produced similar effects on soil physical properties as top-down heating in a lab. However, Stoof et al. (2010) does not discuss whether the soils in their experiment became hydrophobic following top down or muffled furnace heating. In previous muffled furnace experiments, soils were heated to 300 °C (Debano and Krammes, 1966; Glass et al., 2008; Lombao et al., 2015; Mataix-solera et al., 2008), but for a shorter duration than recommended by Stoof et al. (2010).

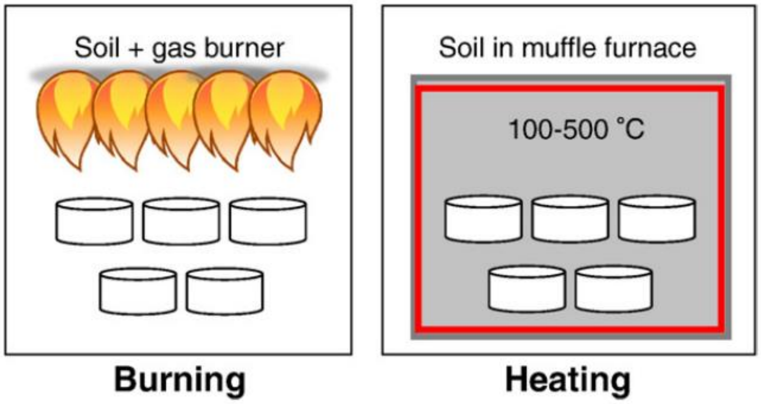

Figure 2-2: Stoof and colleagues (2010) developed an experimental method that compared soils heating to direct soil burning using a propane torch.

Other experiments have used various top down heating approaches to simulate the effects of fire on soil. Cancelo-Gonzalez et al., (2015, 2012) and Debano et al., (1979) used infrared lamps to heat soils. Wieting et al., (2017) used a radiative heat gun to simulate burning conditions. Gabet (2014) and Stoof et al., (2010) burned soil cores using propane torches. Hatten and Zabowski (2010) used propane torches to simulate low severity fires by burning reconstituted soil cores for 15 seconds then used a heat gun to simulate high severity burns. Robichaud and Hungerford (2000) placed soil cores under a propane radiative heater. Within the top-down heating literature, sample ignition was explicitly stated or inferred with each of these top-down heating methods, which allowed the soils direct contact with flames. Table 2-1 shows a comparison of previous soil heating or burning experiments, including the references used to support their approach and metrics used to determine the end point of their studies.

Previous efforts applied various soil moisture controls during experiments. Some researchers air dried soils prior to exposing to heat (Glass et al., 2008; Mataix-solera et al., 2008); other papers did not define the antecedent soil moisture conditions prior to treatment (Marcos et al., 2007; Wieting et al., 2017). Soil water content controls how fire heats soils (Campbell et al., 1995; Debano et al., 1977; Scotter, 1970) and is critical to consider during soil heating experiments. In one experiment, intact soil cores were extracted from the ground then moistened to 5, 15, 30, and 45% moisture content. The cores were then heated using a propane torch. Result showed that heat pulses are absorbed in the first 2.5 cm of soil when volumetric water content is more than 20%, which reduced the amount of root mortality following fire (Busse et al., 2010). When soil is wet, soil temperatures during fire are thought to not exceed 100 °C until the volumetric water content is reduced through evaporation (Campbell et al., 1995; Debano et al., 1977; Scotter, 1970).

Fire's impact on soils have been an interest for the past fifty years. Because fire is difficult to control and to isolate variables, numerous researchers have gained extensive knowledge using laboratory methods to replicate fire's impact on soil (Certini, 2005; Miller et al., 2008; Robichaud and Hungerford, 2000). However, laboratory methods have not always represented wildfire as it occurs in nature (Stoof et al., 2010; Wieting et al., 2017), cannot repeat the effects observed in nature such as hydrophobicity (Badía et al., 2003; Doerr and Moody, 2004; Wieting et al., 2017), and do not always use quantitative metrics.

Within the plant physiology literature, Smith et al., (2017) applied fire radiative energy (FRE) doses (Smith et al., 2016; 2013) to seedlings to reproduced various vegetative burn severities within a laboratory setting. Smith et al., (2017) proposed that fire dosing experiments must: 1) include controls, 2) require measurements of energy, 3) be cross-comparable, 4) be replicable, and 5) be mechanistic. Experiments should be designed to match what occurs in nature. Smith et al. (2016) proposed that FRE treatments, which is the integration of fire radiative power, should be discussed in terms of radiant heat flux density per unit area (J m^{-2}). FRE effects and vegetative burn severity should be discussed relative to the ecosystem process of interest. Smith et al. (2017, 2016) found that 250 g/m^2 and 450 g/m^2 of oven dried western white pine (Pinus monticola) needles produce low and high severity burn conditions, respectively, as it applied to tree mortality following wildfire.

The goal of this effort was to develop and assess a quantitative, measurable, replicable laboratory-controlled experiment that applies FRE treatments to replicate low soil burn severity on soil cores following Smith et al., (2017) methodology. Our method is designed to reproduce what soils experience heating during a wildfire: first organic layers on the soil would combust (direct flame contact), then the soils would continue to be exposed to increased radiative dosing from the combustion of above ground organic material. We demonstrate and assess the ability of the approach to detect the impacts of soil moisture on the rate and timing of heating in undisturbed soil cores.

Methods

Experimental Setup

Experiments were conducted in the University of Idaho Fire Initiative for Research and Education (IFIRE) Combustion Laboratory. The experiment was setup so that soil cores surfaces have direct flame contact to simulate organic layers burning on a soil surface and receive radiant energy to simulate the soil heating originating from other organic material burning such as trees and logs. The combustion of the organic layers added additional FRE exposure to the soils. Oven-dried Western White Pine needles release a known amount of FRE per unit area density (mass per unit area). Western White Pine needles were placed to represent low vegetative burn severity conditions following Smith et al., (2016, 2013). The radiant heating component was simulated by placing the soil cores under an infrared propane heater (Sunstar SG10 Infrared Ceramic Radiant Gas Heater). Temperature was measured using type K thermocouples (Omega Item # TJC1-CAIN-IM025E-150) 1 cm below the radiant heater, on the soil mineral surface (below the organic layer), and at the 2 and 5 cm depths within the soil core. Total fire radiative flux density (FRFD; Quinteire, 2017), a measure of the intensity of the fire, was calculated using equation 1 where ε is the emissivity of the soil and Sunstar Heater assumed to be 0.9; σ is the Stefan-Boltzmann constant in W m^{-2} K^{-4}; t is the time the soils were exposed to heat in seconds; T_{heater} is the average temperature of the heater; F_{12} is a radiative view factor that represent the amount of radiative energy absorbed by the soil core underneath the radiant heater (Blackshear, 1974); and $t=T_{2\,cm\,soil}$ is the time when temperature of the 2 cm depth soil exceeded the temperature threshold. F_{12} is based upon the area of the heater (the emitting source), the area of the soil (the receiving body), and the distance between the two; F_{12} is a unitless value of 1.026. Emissivity of 0.9 is within range of published ceramic radiant heater (Mikron Instrument Company, 2014) values. FRE was quantified by integrating the FRFD across the treatment using equation 2. The Smith et al., (2016; 2013) found that Western White Pine needles applied at a surface density of 250 g per m^{-2} added 0.4 MJ m^{-2} of FRE, which results in a low vegetative severity burn; the ‘Pine needle fuel’ in equation 2 the addition of the FRE released from the Western White Pine needles during the FRE treatments (Smith et al. 2016, 2013). Wooster et al., (2005) found only ~25% of organic material burning on the surface radiates energy towards the soil. The pine needle fuel was reduced following Wooster et al (2005). In this experimental setup, the heater directed all the radiant heat emitted towards the soil and was, therefore, not reduced following Wooster et al., (2005). Fire Radiative Power (FRP), a measure of the energy applied to the whole sample, is calculated in equation 3 (Smith and Wooster, 2005).

$$\text{Fire Radiative Flux Density (FRFD)} = \varepsilon\sigma T_{heater}^{4}F_{12} \qquad (1)$$

$$\text{FRE} = \int_{t=0}^{t=T_{2\,cm\,soil}>100\,^{\circ}C} FRFD\,\text{dt} + 0.25 * \text{Pine Needle Fuel} \qquad (2)$$

$$\text{Fire Radiative Power } (FRP) = \text{FRFD} * Area_{soil} \qquad (3)$$

The soil cores were placed approximately 25 cm under the radiant heater once the temperature of heater stabilized. After a short period of time (<5 seconds) the heater ignited the organic material on the cores. The goal of this effort was to apply the same amount of FRE to the soil to replicate a low soil burn severity fire, which is analogous to a prescribed burn (Thies et al., 2005). FRE values resulting in vegetative burn severity are published. However, FRE that result in a low soil burn severity are not found in the literature. Debano et al., (1977) and Wieting et al., (2017) stated that 2 cm soil temperatures at 100 °C and 200 °C resulted in a low and high soil burn severity, respectively. In this experiment, we focused solely on the low soil burn severity. Therefore, using this soil temperature as an indicator of low severity, soil cores where heated to the 100 °C threshold and then FRE was back calculated by integrating the FRP from the time the soil was placed under the heater. The variability in required FRE to reach 100 C was described using three thresholds based on the average and standard error of the soil temperature at a particular time into the experiment. A lower soil temperature threshold, representing a minimum time required to reach 100 °C, was defined as the cumulative FRE whenever the average temperature plus the standard error first exceeded the 100 °C threshold. Similarly, an upper soil temperature threshold representing a maximum time required to reach 100 °C was defined as the cumulative FRE whenever the average temperature minus the standard error exceed the 100 °C threshold. The average temperature threshold was when the average 2 cm temperature for each treatment exceeded 100 °C. In total, FRE was determined for six differing thresholds (i.e., $\text{lower}_{\text{dry}}$, $\text{average}_{\text{dry}}$, $\text{higher}_{\text{dry}}$, $\text{lower}_{\text{wet}}$, $\text{average}_{\text{wet}}$, $\text{higher}_{\text{wet}}$). FRE at time each threshold was met were compared between the wet and dry soils. Statistical significance was determined between FRE in each differing threshold between the wet and dry samples using Student's T-test. Figure 2-3 shows the sample treatment process in a conceptual diagram. Figure 2-2 shows the soil core collection and preparation for burning.

Soil Sample Collection and Preparation

Soil samples were collected from the Fernan watershed within the Coeur d'Alene district of the Idaho Panhandle National Forest near Coeur d'Alene, Idaho. The Fernan watershed is 4,225 hectares with mountain gradients between 40 to 60% (Idaho Department of Environmental Quality, 2013) and composed of evergreen forest land (86%) and shrub/scrub (10%) land (Homer et al., 2015). Fernan receives an average of 29 inches of rainfall and 59 inches of snowfall (Idaho Department of Environmental Quality, 2013). Soil samples were collected in forested regions of the watershed.

Ten soil cores were collected from a silt loam soil from the Typic Vitrixerands family (Soil Survey Staff, n.d.) approximately 1 meter apart in a 4 by 5 gridded pattern centered at 43.88°-116.67° (WGS84). Samples were collected using an 8-inch (20.3 cm) PVC soil corer inserted ~10 cm into the ground. Around the soil corer was dug out and a metal plate was inserted underneath the corer through the soil to extract an intact sample profile sample. Samples were transported and stored in the corer to ensure that the soil profiles remained undisturbed throughout the process.

Once in the lab, two soil moisture treatments were applied to the soil cores to test the impacts of soil moisture on soil heating. Five cores were dried at 40 ℃ for 24 hours and 5 cores were saturated until freely draining from the bottom then allowed to drain for 24 hours (i.e., field capacity). Before and after burning, the soil cores were weighed, and soil moisture was measured using Acclima TDR sensors. The cores were then prepared for FRE treatments by applying the oven dried Western White Pine needles on the top of the mineral surface. The pine needle fuel allowed the soils to have direct flame contact with the mineral soil and released 0.4 MJ m^{-2} of radiant energy following combustion (Smith et al., 2013). Previous unpublished experiments found that the pine needle fuel alone did not provide enough energy to reproduce soil burn severity conditions; therefore, additional energy from the heater was needed. Finally, thermocouples were place on the mineral surface, 2 cm, and 5 cm depth.

Table 2-1: Comparison of previous laboratory-based soil heating and soil burning experiments. Numerous standards, metrics, and original references have been used across the soil community.

Paper	Temperature Range (°C)		Original Reference	Depth (cm)	Burn Severity Achieved	Average Burn Time
Robichaud and Hungerford, 2000	100 to 150 250 to 300 400 to 450		Wells et al., 1979	0 to 10 for all cases	Low Medium High	Not Reported Not Reported High severity target took several hours to achieve
Gabet, 2014	250 450 650 800 975 1025	350 500 550 750 875	Debano et al., 1979	Surface	N/A	5 min 10 min 15 30 min 45 min 60 min
Stoof et al., 2010	900		Chandler et al 1983 and Glass et al 2008	Surface		5 min
Cancelo-Gonzalez et al., 2012	200 400		Not Listed	1 1	Not Listed	15 to 20 min; 75 to 80 min 40 to 50 min; 100 to 110 min
Cancelo-Gonzalez et al., 2015	200 400		Chandler el al 1983 for both	1 1	Medium High	85 to 90 min 100 to 110 min
Wieting et al., 2017	>100 >200		Certini, 2005	1 to 2 1 to 2	Low High	40 min on average Stopped after an hour if target was not achieved
Hatten and Zabowski, 2010	N/A N/A		Post treatment assessment (Neary et al., 1999; Key and Bensen 2006)	N/A N/A	Low Medium High attempted but not achieved	O horizon reconstructed Dried O horizon reconstructed. 30 min exposure to heat gun

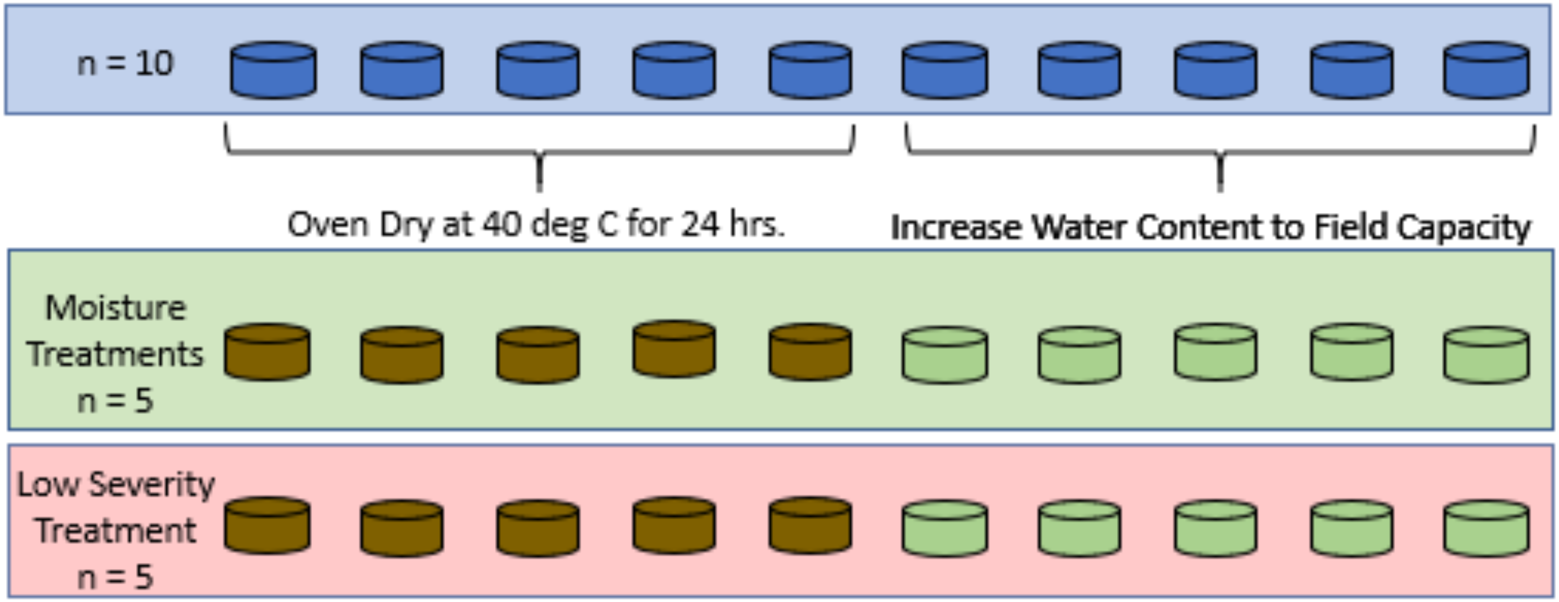

Figure 2-2: This figure shows the soil core treatment. Ten (8 in) soil cores were collected from the same hillslope in the Fernan Watershed. Soil moisture treatments were applied to the cores; five cores were oven dried at 40 °C for 24 hrs. and five cores were increased to field capacity. Low severity burn treatments were applied to samples. In total 5 soil cores were treated in each treatment combination (low severity dry, low severity wet).

Figure 2-3: These pictures show the soil core process. From left to right, the first picture shows the collection of the soil core. The second picture shows how the metal plate was inserted below a soil core to maintain the soil structure. The third picture shows a soil core with the Western White Pine needles. The last picture shows a soil core with the thermocouples installed ready to be placed under the heater.

Results

Soil Core Temperatures and Moisture

The wet samples took longer to reach the 2 cm 100 °C temperature threshold than the dry samples. In the dry samples, temperatures reached 100 °C at the 2 cm depth as early as 1.5 minutes (lower limit) and as late as 3.8 minutes (upper limit) after ignition. On average, the dry soils passed the temperature threshold after 2.25 minutes. The wet samples reached the temperature threshold as quickly as 4.5 minutes (lower limit) and as long as 7 minutes (upper limit). On average, the wet samples reached the temperature threshold after 5.25 minutes. Figure 2-5 shows the average 2 cm depth temperature profiles for the dry and wet samples compared to the 100 °C threshold for a low soil burn severity. FRE treatments were applied for an average of 9.5 minutes. The 5 cm soil temperature never reach 100 °C; Figure 2-6 shows a plot of a dry soil temperature profile during FRE treatment.

Soil moisture was measured before and after FRE treatments. The soil moisture in each of the dry samples was 0% before and after treatment. The average soil moisture in the wet samples was 12.7% by volume before burning. Following FRE treatments, the average soil moisture in the wet samples decreased to 10.2% on average. The wet samples lost an average of 155 g of water during the burning experiment.

Soil moisture was measured before and after FRE treatments. The soil moisture in each of the dry samples as measured by the TDR was 0% before and after treatment. The average soil moisture in the wet samples was 12.7% by volume before burning and decreased to 10.2% after treatment. The wet samples lost an average of 155 g of water during the burning experiment.

Resulting Fire Radiative Power and Energy Inputs to the Soil Cores

Average FRFD and FRP applied to the dry samples was higher (89.2 kW m^{-2} and 2.9 kW, respectively) than in the wet samples (73.7 kW m^{-2} and 2.4 kW, respectively); this finding is significant (p-value 1.9 x 10^{-3}). On average, the dry samples received 12.2 MJ m^{-2} of FRE. The FRE treatments in the dry samples ranged between 8.2 to 20.5 MJ m^{-2} in the lower and upper limits, respectively. The wet samples received an average of 32.1 MJ m^{-}2 of FRE. The lower and upper limits of FRE in the wet samples ranged from 27.4 MJ m^{-2} to 42.9 MJ m^{-2}. Difference in FRE at each time interval (the time when temperatures passed the 100 °C threshold for the lower$_{dry}$, average$_{dry}$, higher$_{dry}$, lower$_{wet}$, average$_{wet}$, higher$_{wet}$) were statistically significant between the wet and dry samples at an $\alpha = 0.05$ level except for the average dry threshold of 2.3 minutes. The statistical significance shows that that the soil moisture impacted the energy balance in the soils. Table 2-2 summarizes the average FRP, lower, average, and upper time limits and the FRE associated with each. Figure 2-7 shows a plot of the FRE applied to the dry and wet soil samples. Published FRE estimates from in-situ FRE measurements are also included in the figure for comparison purposes.

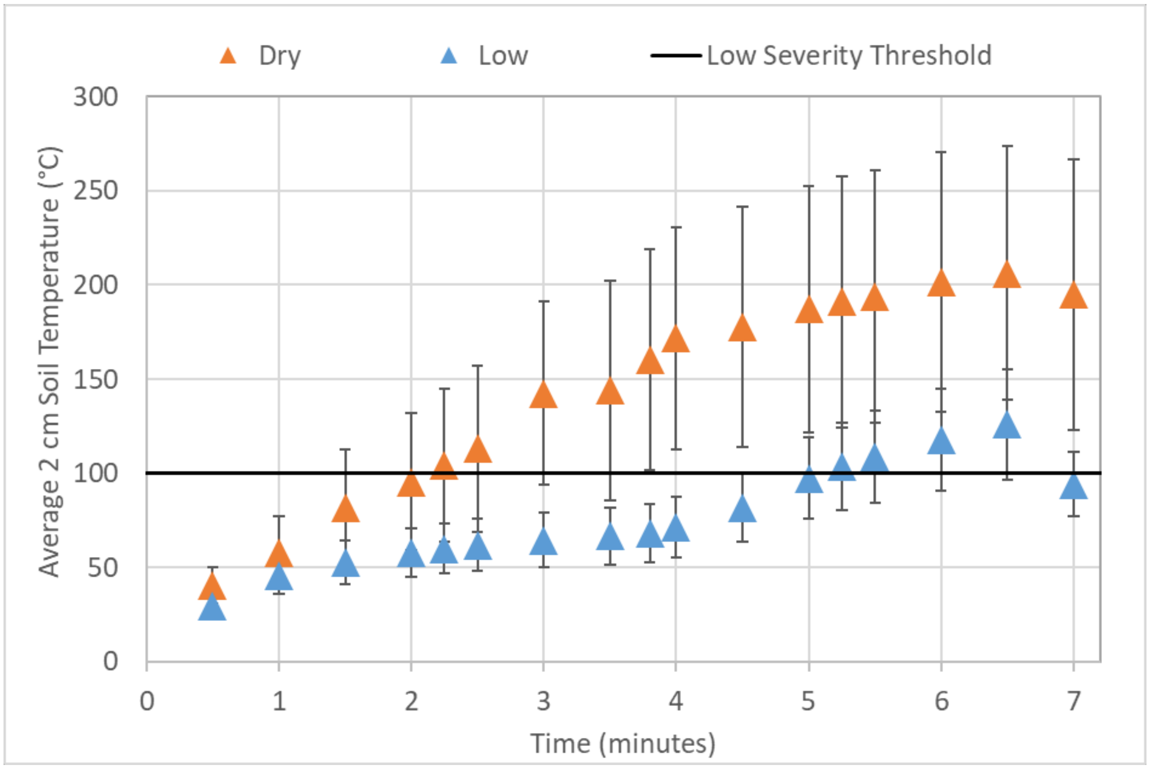

Figure 2-5: The average 2 cm soil core temperature observations are shown for the dry (shown in orange) and wet (shown in blue) samples. The error bars represent one standard error of the temperatures observed at each time interval. The black line highlights the 100 °C low soil burn severity from Debano et al., (1977) and Wieting et al. (2017).

Discussion

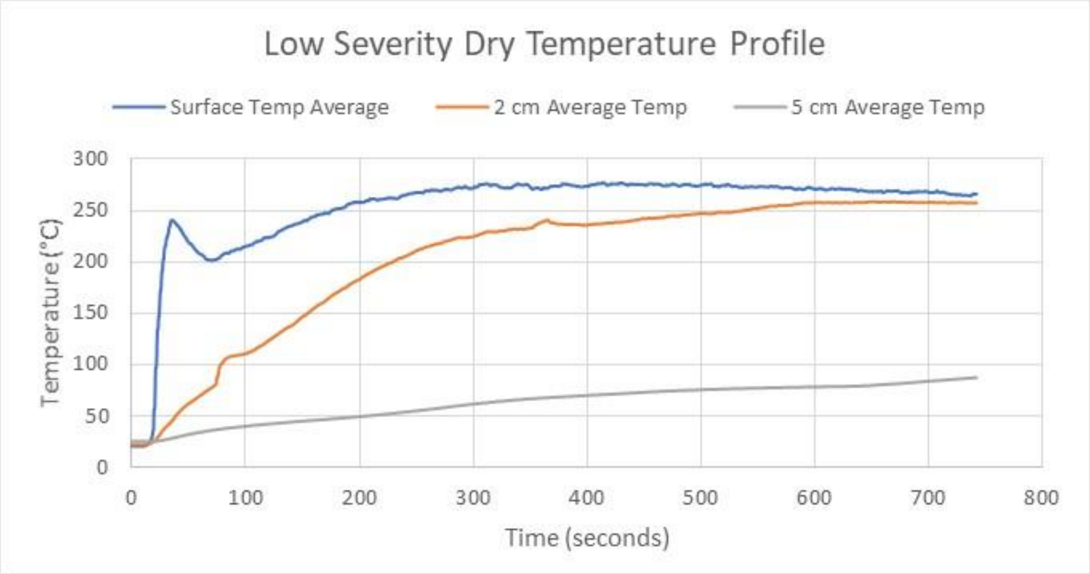

Figure 2-4: Temperature profile from a low severity dry sample treatment. The blue line shows the surface temperature of the soil. The orange line shows the temperature measured at the 2 cm depth. The gray line shows the temperature measured at the 5 cm depth.

More FRE was required to reach temperature thresholds with the wetter samples than with the drier samples, matching previous studies (e.g., Campbell et al., 1995; Debano et al., 1977; Scotter, 1970) and as expected since part of the FRE (2.60 MJ of energy required to evaporate 1 kg of water) was used to evaporate water. Previous research has found that soils do not reach over 100 °C until soil moisture is lower than 0.02% by volume (Campbell et al., 1995). Soil temperatures exceeded 100 °C and moisture decrease following FRE treatments to 10.2% by volume, but not decrease nearly as large as noted by Campbell et al., (1995). The soil moisture was taken as an average soil moisture within the core. More than likely, the top 2 cm were extremely dry (as evident by the temperatures increasing above 100 °C). The fact that the 5 cm temperatures never reached 100 °C indicates that the lower part of the soil core retained soil moisture in the wet samples. The wet soils also took 3 minutes longer, on average, to heat up to 100 °C. On average, the wet samples lost 155 g of water, which required 350 kJ of energy to evaporate. The average FRFD in the wet samples was 73.7 kW m^{-2}. Therefore, the latent heat of vaporization is anticipated to take 2.4 minutes, matching closely to the 3-minute time lag that we observed.

Table 2-2: Average Fire Flux Density (FRFD; kW m^{-2}), Fire Radiative Power (FRP; kW), Temperature (℃), and Fire Radiative Energy (FRE; MJ m^{-2}) are presented for the lower limit, average, and upper limit found when the soil core temperature passed the 100 ℃ threshold for representing a low soil burn severity. The lower limit is defined as the time when the 2 cm average soil temperature plus the standard error exceeded the threshold. The average represents when the average 2 cm soil temperature exceeded the threshold. The upper limit represents when the average temperature minus the standard error crosses the temperature threshold. * indicates a significant difference between the wet and dry samples at an α = 0.05 level.

	Average		Lower Limit		Average		Upper Limit	
	FRFD (kW m^{-2})	FRP (kW)	Time (mins)	FRE (MJ m^{-2})	Time (mins)	FRE (MJ m^{-2})	Time (mins)	FRE (MJ m^{-2})
Dry	89.2	2.9	1.5	8.2*	2.3	12.2	3.8	20.5*
Wet	73.7	2.4	4.5	27.4*	5.3	32.1*	7.0	42.9*

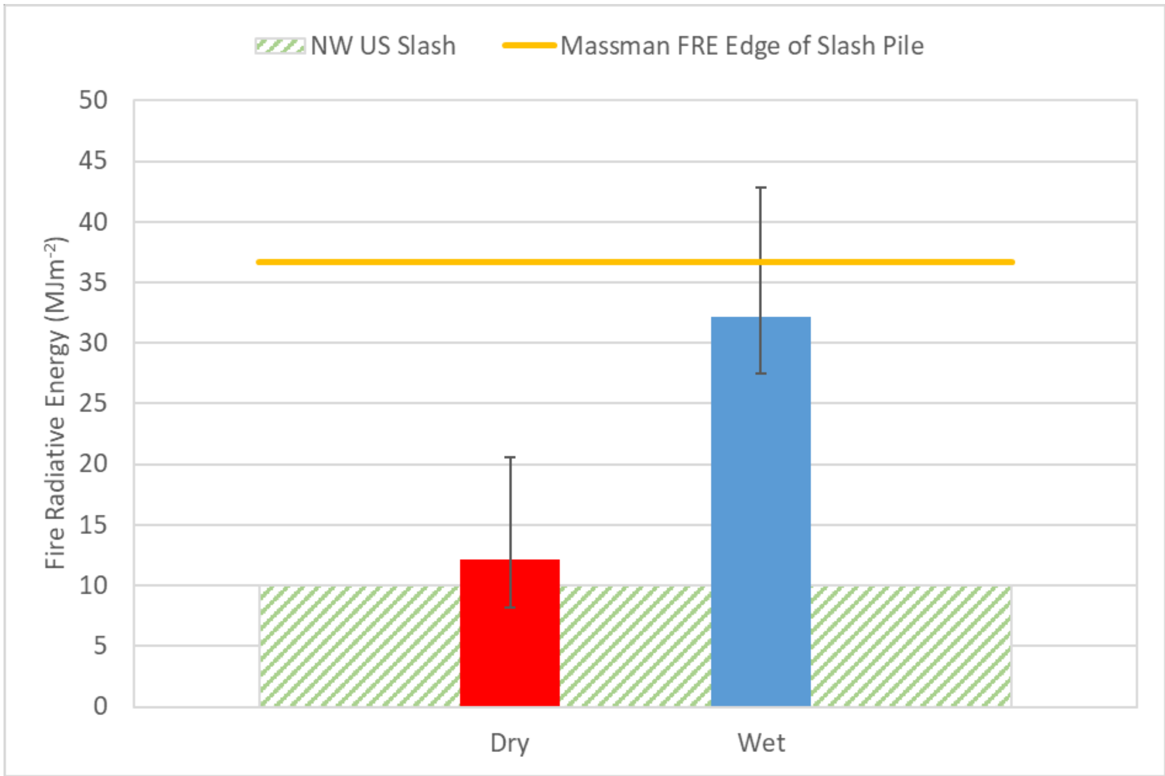

Figure 2-7: Fire Radiative Energy (FRE) amounts applied to the dry (shown in red) and wet (shown in blue) soil cores during the simulated fire experiment. The error bars show the upper and lower amounts of FRE applied to the soils when the soil cross the 100 ℃ threshold. For comparison FRE estimates are shown for a Northwestern United States slash piles (NW US Slash; Smith et al., 2017; Sparks et al., 2017) and from the edge of a large slash pile in the Manitou Experimental Forest (Massman and Frank 2004).

Soil temperature from the Debano et al., (1977) were used as a surrogate of low soil burn severity to determine the end point of the treatment. Debano et al., (1977)'s temperature thresholds were generated in a region dominated by granite parent material soil whereas an andic soil was used in this study. Thermal conductivity soil sandy soils tend to be higher than the thermal conductivity of finer textured soils (Abu-Hamdeh and Reeder, 2000), like the silt loam used in this experiment. The amount of FRE needed to reach the 100 °C in the sandy soils with a higher thermal conductivity is presumably less in the sandy soils than in the finer textured soils tested in this experiment.

Andic soils have a high water-holding capacity (McDaniel and Wilson, 2007), which directly impacts how quickly a soil temperature increases during fire (Campbell et al., 1995). The soils volumetric water content of the soil cores was measured using a TDR as an average soil moisture vertically (e.g., the probe was inserted such that it measured water content from the 1 cm depth to the 4 cm depth) across the soil core before and after burning. If the volumetric water were measured horizontally (e.g., the probe was inserted to measure a single soil depth), we would expect to see that the soil moisture to be very dry in the near surface and increase with depth. As water content increases in the soils, we would also anticipate an increase in time for the soils to reach the temperature threshold.

Applying FRE treatments to soils requires a balance between the duration (time exposed) and the intensity (FRFD) of the fire. The FRFD applied to these soils averaged 82 kW m^{-2}. FRFD and FRP varies based upon fuel load and fuel moisture content (Wooster et al., 2005; Roberts et al., 2005). FRFD values in the literature are often related to prescribed (e.g, Sparks et al., 2017) or experimental burns (e.g, Kremens et al., 2012). Broadcast burning in a mix-oak forest noted FRFD values around 20 kW m^{-2} (Kremens et al., 2012). In the northwest slash piles burn had observed FRFD values peak near 16 kW m^{-2}. However, Sparks et al., (2017) noted that 97% of the combustion was smoldering-dominated. The FRFD rates in this experiment are much higher than previous values from controlled burns. Interestingly, we observed the FRFD values were lower in the wet soils than the dry soils even though the heater was setup the same between treatments. The evaporating soil moisture not only slowed the heating of the soils by 3 minutes (as discussed earlier), but we also speculate that the evaporating soil moisture was cooling the soils and intercepting FRE transmitted to the wet samples.

Since FRE values that result in low soil burn severity have not been published, we calculated FRE by integrating the FRFD over the time it took for the 2 cm soil depth to reach 100 °C. In the dry samples, FRE ranged from 8.2 to 20.5 MJ m^{-2} and 27.4 to 42.9 MJ m^{-2} in the wet samples. In the in-situ field experiments, FRE has been estimated by modeling the fuel consumption (Sparks et al., 2017), measured using infrared sensors (Kremens et al., 2012), or estimated using remote sensing (Li et al., 2018). FRE observed in nature vary based on numerous factors (e.g., fuel type, fuel consumption, moisture content). In savannah grasslands, having much less biomass than a coniferous forest, estimates of FRE of 0.14 MJ m^{-2} have been published (Smith et al., 2016). Prescribed burns in the a ponderosa pine stand in the North-western United States slash piles (Sparks et al., 2017) and mixed-oak forest surface fires (Kremens et al., 2012) found published FRE estimates upwards of 10 MJ m^{-2}. In the Manitou Experimental Forest, measurements of soil temperature and heat flux were measured under slash pile ~6 meters tall and ~9 meters in diameter (Massman and Frank, 2004). FRE from the center of the slash pile range upwards of 77 MJ m^{-2} and 37 MJ m^{-2} near the edges (personal communication with Bill Massman). Using remote sensing to estimate FRE from 445 wildfires, Li et al., (2018) found FRE estimates as high as 15 MJ m^{-2}. While the observed FRE may seem high, soil burn severity was never categorized after burning in the previous studies. Thus, we do not have direct basis for comparison between FRE in the lab and FRE leading to low soil severity burn conditions.

In this experiment, the FRFD was high compared to the previous studies but the FRE fell within range of published FRE values from previous fires and prescribed burns. FRFD density could be decrease by using a heater that does not produce as much heat or by increasing the distance between the heater and the soils. For example, the heater was 20 cm above the samples in this experiment; if the heater was 0.5 m above the samples, the F_{12} would have been reduced by ~33%. The lower radiative view factor would decrease the FRE on average by ~35% and would require 2.2 more minutes of exposure to achieve the same FRE. Additionally, the amount of FRE applied to the soil in this experiment was controlled by the amount of time (t) that each soil core was exposed to the ceramic heater. In this experiment, the soils were burned for 2 to 6 minutes total. In contrast, the Northwest slash piles burned for two days. Increasing FRP might rapidly increase soil surface temperature but the propagation of this energy into the soil might be limited similarly to relationship between BBQ temperature and internal temperature of a steak. Post-fire soil burn severity may change when burning soils under a high intensity fire (or heater in this experiment) and a short time compared to a low intensity fire for a longer duration.

Management Implications

In this experiment, we developed and tested a standardized, quantitative approach to reproduce fire on soils in a laboratory setting. The method exposes soils to direct flame contact and heats soils in a top-down fashion, similar to how soils are heated in-situ during wildfire and prescribed burns. The method can reproduce both low and high severity conditions by varying the amount of time that a soil is exposed to a radiant heater. The method allows land managers to test the impact of fire, whether prescribed or natural, on soils in a laboratory before an event occurs so that they can preemptively develop management plans. Results for our study showed that soil temperature remained lower when wet. This result is consistent with previous studies that showed wet soil absorbed heat pulses better than dry soils (Busse et al., 2010; Campbell et al., 1995). The lag time required between the wet and dry soils to reach 100 °C can be largely explained by the amount of latent heat energy required to evaporate the observed mass of water lost in the experiment. This research suggests that prescribed burns on wet soils would likely result in less soil burn severity than prescribed burns on dry soils.

One of the challenges in this study was protecting the thermocouples and keeping them inserted in the soils as the soil cores burned. The structural changes in the soil cores as it burned could have been remediated by conducting the burn experiment in-situ. Although this research was conducted in a lab, it is possible to conduct this experiment in-situ. Adjacent to the undisturbed soil, a pit could be dug so that thermocouples could be inserted into the soil. The infrared heater could be setup above the soil and ran for the appropriate amount of time.

Conclusions

In this paper, we developed and assessed a laboratory method to test the effects of fire on soil. We demonstrated the ability of the method to distinguish the effects of soil water content on soil heating. Previous soil heating studies have used various heating methods, differing metrics to determine an experiment's end point, and have not always exposed soils to direct flames. By combining direct fire flame exposure and soil heating using a radiative heater, soils in a lab are exposed to the same conditions that would occur during a wildfire. Using a standard fuel load and soil temperature measurements, fire radiative energy dosing can be measured. This method meets Smith's (2017) criteria for laboratory burning experiments that they must: have controls, require measurements, be cross-comparable, be replicable, and be mechanistic. By applying FRE to soils, it allows for a mechanistic process to apply measurable amounts of energy to a soil—standardizing the process testing the impact of fire to soils in a laboratory. Using this method, we observed a 3-minute lag in the time to burn wet vs dry samples which aligned well with the time required to evaporate the soil water based on FRP used in the experiment. We measured a difference in FRE of 32.1 vs 12.2 MJ m^{-2} in wet vs dry soil which we used to develop recommendation for fire exposure time.

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Chapter 3: Forest Soils Response to Fire Radiative Energy Dosing

Abstract

Wildfires have been increasing in magnitude and frequency throughout the west. Fires are well documented to increase erosion rates, alter physical properties of soils, and impact water quality. Previous research quantified shifts in soil nitrogen and carbon. However, less is known about the impact of fire on the form, concentration, and content of soil phosphorus. In this research, we quantify the shifts in soil total carbon (TC), water extractable phosphorus (WEP), and total phosphorus (TP) in an andisol forest soil from the Pacific Northwest before and after simulated wildfire. Two moisture treatments were applied (field capacity and oven-dried at 50°C for 24-hours) to the soil prior to simulated wildfire to assess the management strategy that targets prescribed burned under wetter soils conditions. Wildfire treatments were applied using a fire radiative energy (FRE) approach in a laboratory. TC and WEP concentration and content decreased following treatment in the wet and dry samples. TC decreased by 37% and 58% in the wet and dry treatments (p-value < 0.001). WEP decreased by 50% in the wet treatments and 30% (both at a p-value < 0.001) in the dry treatments. Results indicate that applying prescribed burns while the soil is wet may improve management of WEP—a critical limiting nutrient in many alpine watersheds.

Introduction

Large, intense wildfires leave a scarred landscape highly susceptible to landslides, debris flows, increased runoff and erosion—transporting both nutrients and valuable top soil (DeBano and Neary, 2005; Moody and Martin, 2001; D. G. Neary et al., 2005). Erosion strips steep slopes of topsoil and valuable nutrients necessary for forest regeneration and ecosystem recovery. Downstream water bodies fill with sediment enriched with nutrients (Boerner, 1982; Robichaud, 2000; Tiedemann et al., 1978), impairing spawning habitat (Benda et al., 2003; Lyon and O'Connor, 2008), changing trophic states in lake systems (Mceachern et al., 2000; Schindler, 2009; Wright, 1976), and increasing algae productivity (Silins et al., 2014). Post-fire long-term water quality impacts of wildfire (Emelko et al., 2016) can threatened the quality of water in municipalities dependent upon surface water reservoirs for drinking water (Smith et al., 2011).

Understanding post-fire landscape dynamics are critical for stabilizing soil and protecting downstream water quality (Robichaud, 2000; Robichaud et al., 2009). Post wildfire erosion rates can be 1,000 times greater than pre-fire conditions (Elliot et al., 2006). Forest soils are most vulnerable to erosion immediately after fire and conditions are generally assessed soon after the burn. Burned Area Emergency Response (BAER) teams complete a rapid assessment of burned areas using the best available information, landscape based site assessments, predictive modeling, and professional expertise to determine if landscape stabilization is needed (Robichaud et al., 2009). BAER teams use decision support tools (e.g., ERMiT, Robichaud, 2003; WEPP, Flanagan and Nearing, 1995; WEPP-BAER) that quickly assess where management practices are needed to reduce sedimentation.

Managing impacts of wildfire within a landscape requires a firm understanding of how fire affects soil physical and chemical properties. Previous efforts have quantified the effect of soil heating on a soil's physical properties. Soil heating increases soil aggregate stability (Garcia-Corona et al., 2004), decreases hydraulic conductivity (Certini, 2005; Debano, 2000; Garcia-Corona et al., 2004), increases thermal conductivity in dry soils and decreases thermal conductivity in wet soils (Lombao et al., 2015; Massman et al., 2008), and creates hydrophobic soil horizons (Certini, 2005; Debano, 2000; DeBano et al., 1976; Garcia-Corona et al., 2004; Massman et al., 2008; Neary et al., 2005). Many of the physical changes are related to the duration and intensity of exposure to fire (Garcia-Corona et al., 2004; Lombao et al., 2015), and initial water content of the soils before the fire (Busse et al., 2010; Massman et al., 2008).

Fire also alters a soil's chemical properties. Fire can decrease the amount of soil organic matter through volatilization (Adams, 2013; Beringer et al., 2003; González-Pérez et al., 2004; Lombao et al., 2015; Miller et al., 2008; Wondzell and King, 2003) and becoming a source of atmospheric carbon (Beringer et al., 2003). Ammonium (NH4+) and nitrate (NO3-) soil concentrations have been found to decrease following forest fire (Certini, 2005; Glass et al., 2008) and increased in localized surface runoff (Johnson et al., 2014; Miller et al., 2008). Erosion intensifies following fires (Adams, 2013; Debano, 2000; Lombao et al., 2015; Moody and Martin, 2001; Wagenbrenner et al., 2015), which increases transport of both dissolved and particulate bound nutrients. While carbon and nitrogen soil dynamics are better understood following fire, less is known about how fire affects the availability, form, and transport of soil phosphorus (P). In some cases, the availability (Cade-Menun et al., 2000) and mobility (Miller et al., 2008; Johnson et al., 2014) of biologically P increased.

Assessing the impact of wildfire on soil properties is difficult. Fire is highly variable and many variables (e.g., fire intensity, temperature) cannot be controlled (Lombao et al., 2015). Many authors have turned to soil heating experiments to test the effect of temperature exposure on soils' physical and chemical properties (Cancelo-Gonzalez et al., 2015, 2012; Garcia-Corona et al., 2004; Glass et al., 2008; Lombao et al., 2015; Parlak, 2011; Serrasolsas and Khanna, 1995). Soil heating experiments indicate total C concentration (Glass et al., 2008) and content (Lombao et al., 2015) decrease following high intensity or long duration fires. In addition, it has been observed that NO3- and NH4+ concentration increases (Glass et al., 2008), Fe+ and Al+ leaching increases (Cancelo-

Gonzalez et al., 2015), and biologically available soil P increases following exposure to temperatures above 200 °C (Parlak, 2011). Serrasolsas and Khanna (1995) found labile inorganic P (extracted using Bray-I method) increased when temperatures increased more than 250 °C. While many of the previous studies provide insight to soil changes following heating, soil heating through the use of a muffle furnace does not expose soil to the same conditions as a wildfire (Stoof et al., 2010; Wieting et al., 2017) and cannot repeat the effects observed in nature such as hydrophobicity (Badía et al., 2003; Doerr and Moody, 2004; Wieting et al., 2017), which can exacerbate particulate P transport (Simmonds et al., 2017).

Soil water content is highly variable within soil and has been found to control how heats propagates through soils (Campbell et al., 1995; Debano et al., 1977; Scotter, 1970). In a series of experiments, Busse et al., (2010) found that heat pulses were absorbed in the first 2.5 cm of soils and reduced the amount of root mortality when the volumetric water content was more than 20% in sandy loam, loam, and clay loam soils. Soil temperatures during fire do not exceed 100 °C until the volumetric water content is reduced through evaporation (Campbell et al., 1995; Debano et al., 1977; Scotter, 1970).

Many alpine lakes tend to be P limited (Schindler, 1977). Sensitive and high-profile lakes such as Lake Tahoe, CA/NV (Goldman 1988), Fernan Lake (IDEQ 2013), and Coeur d'Alene Lake, ID (Woods and Beckwith 1997) are examples of P limited systems surrounded by forests. If a fire were to impact these areas, P load may increase. Excess P loading can lead to the development of harmful algae blooms—like the blooms currently faced at numerous lakes around the country (e.g., Hayden Lake, [Kootenai Environmental Alliance, 2012]; Lake Huron, Lake Erie [Vanderploeg et al., 2001]; Fernan Lake [Idaho Department of Environmental Quality, 2013]). To protect sensitive alpine lakes, it is critical to understand how fire affects soil P dynamics.

Soil P concentration tends to be highest in the finest particle size classes within a particular soil (Geisseler et al., 2011; Rubaek et al., 1999; Tiessen and Stewart, 1983). Previous research found that the strength of the bond between P and soil particles increases with decreasing particle size (Geisseler et al., 2011; Rubaek et al., 1999). Understanding the P distribution within a soil can aid in downstream water management decisions, especially post-fire when landscapes are more highly susceptible to soil erosion (Adams, 2013; Debano, 2000; Martin and Moody, 2001)leading to increased TP loading to downstream water bodies (Oliver et al., 2012; Simmonds et al., 2017).

Prescribed burns are commonly used to manage fuel loads (Moritz et al., 2014; Sackett, 1975; Stephens et al., 2012) and protect life and property (Penman et al., 2011). Prescribed burns are an effective means to reduce fire severity (Reinhardt et al., 2008) and protect ecosystem services such as downstream water quality (Elliot et al., 2016). Prescribed burns are often considered to be analogous to low severity burns (Thies et al., 2005). The seasonal timing of prescribed burns is important as it can impact tree mortality (Swezy and Agee, 1991; Thies et al., 2005). Results conflict in the literature regarding the optimal season to do prescribed burns. While prescribed burns protect landscapes and reduce future fire severity, less is known about the impact on soil phosphorus pools.

The objective of this research is to quantify changes in the form, concentration, and content of P and C in a forest soil following a simulated wildfire from both organic duff layers and mineral soil within a controlled lab setting. Since soil moisture is known to control soil heating during a fire and can be an important factor driving potential difference in phosphorus form and concentration between wildfires and prescribed fires, we investigated the impact of soil moisture by applying two soil moisture treatments (soil moisture increased to field capacity and oven dried for 24-hours). We hypothesized that higher soil moisture would retard the shifts in soil P following wildfire exposure. Knowledge gained from this study will be used to inform and improve nutrient loading for BAER team models and provide insight on impacts of prescribed burns on the risk of P transport.

Methods

Site Description and Sample Collection

Organic matter (OM) samples and a bulk Typic Vitrixerands (Soil Survey Staff, n.d.) soil samples were collected from the Fernan watershed within the Coeur d'Alene district of the Idaho Panhandle National Forest near Coeur d'Alene, Idaho. The Fernan watershed is 4,225 hectares and composed of evergreen forest land (86%) and shrub/scrub (10%) land (Homer et al., 2015). Soil samples were collected in forested regions of the watershed (47.72°, -116.67° WGS 1984).

Fire Radiative Energy Treatments

Wildfire was simulated in the lab by placing the samples under a propane radiant heater (Sunstar SG10 Infrared Ceramic Radiant Gas Heater). Fire radiative power (FRP; kW m^{-2}) and total Fire Radiative Energy (FRE; MJ m^{-2}) over the experiment was calculated using equations 1 and 2. FRP is calculated using equation 1, where ε is the emissivity of the soil and Sunstar Heater assumed to be 0.9; σ is the Stefan-Boltzmann constant in W m^{-2} K^{-4}; t is the time the soils were exposed to heat in seconds; T_{heater} is the average temperature of the heater and F_{12} is a radiative view factor (Blackshear, 1974). Emissivity of 0.9 is within range of published ceramic radiant heater (Mikron Instrument Company, 2014) values. FRE was quantified by integrating FRP throughout the duration of the experiment (equation 2) plus pine needle fuel is the FRE released from the Western White Pine needles determined following the Smith et al., (2016, 2013) approach. The pine needle fuel added 0.4

MJ m^{-2} and 1.2 MJ m^{-2} for the low and high severity treatments, respectively. Wooster et al., (2005) found only ~25% of the radiative energy radiates towards the soils. The pine needle fuel was reduced following Wooster et al (2005).

$$\text{Fire Radative Power (FRP)} = \varepsilon\sigma T_{heater}^{4} F_{12} \qquad (1)$$

$$\text{FRE} = \int_{t=0}^{t=t_{end\ of\ treatment}} FRP\ \text{dt} + 0.25 * \text{Pine Needle Fuel} \qquad (2)$$

Litter Samples

Five intact forest floor litter samples (litter) were collected by inserting a 0.6 m x 0.6 m piece of 64 mm (¼ inch) plywood between the mineral soil and organic matter following similar methods to Loupe et al., (2007). Sub-samples of the litter were taken and submitted to A&L Great Lakes Laboratories (Fort Wayne, ID; 260-483-4759) for total carbon (TC), water extractable P (WEP), and total P (TP). TC was determined using a Leco sampler that determines soil carbon via combustion following Methods of Soil Analysis (MSA) Part 3 (1996, pages 963-977). TP was determined following a perchlorate digestion using an ICP following MSA number 9 (1965 pages 1036-37). WEP was determined via a water extraction where soil was placed into deionized water and shaken then filtered. The filtrate was analyzed for P using an ICP.

Samples were prepared for the laboratory fire treatment by determining the litter sample area and placing oven-dried Western White Pine needles on top of the litter samples at a mass application of 400 g m^{-2}, following Smith et al., (2016, 2013). Samples were weighed to the nearest gram. Three type K thermocouples (Omega Item # TJC1-CAIN-IM025E-150) were inserted beneath the pine needles, in the middle of the litter, and beneath the litter.

Figure 3-1: Forest Floor Organic Matter Sample Processing (left to right). First picture shows the collection of the forest floor organic matter. Second picture shows a sample prepared for fire radiative energy dosing. Third picture shows a post-burn sample.

Litter samples were placed under an infrared propane heater. FRP and FRE were calculated following treatment. Temperature of the infrared heater was measured in the flames of the heater approximately 1 cm below the surface of the heating plates using a thermocouple. Samples were moved under the heater once the heater temperature stabilized. Samples ignited within 5 seconds after being exposed to the heater. Sample temperature was measured every 0.5 second until the fire naturally burned out. Samples burned on average for 10.8 minutes. Thermocouples were removed and the remaining sample material was re-weighed. Sub-samples were collected and analyzed for TC analysis, WEP, and TP.

Total Carbon, Water Soluble Phosphorus, and Total Phosphorus Mass Balance Approach

To understand the mass of TC, WEP, and TP within the organic and mineral soil horizons within a forest soil, 49 kg of a bulk soil sample and five 2.5 cm soil bulk density samples were collected from the top 5 cm of mineral soil from the Fernan Watershed. The bulk soil sample size distribution was determined for the coarse (>1 mm) and fine (< 1 mm) size fractions. Roots in the soil were removed from the analysis. Coarse and fine size fractions were individually blended and five sub-samples were taken for analysis using cone and quartering (Raab et al., 1990; Schumacher et al., 2014). Samples were submitted to A&L Great Lakes Laboratories for TC, WEP, and TP analysis using the same methods described above. An average wet bulk density was determined from the 5 collected soil bulk density samples. Following burning, the cores were re-sieved and sub-samples were collected for analysis following the same methods as the pre-burn samples.

To reduce the natural variability in soil structure and soil texture between soil samples, twenty reconstituted soil cores were constructed. The reconstituted cores were split by coning and quartering (Raab et al., 1990; Schumacher et al., 2014) each size fraction to the proper mass to match the original distribution determined (coarse vs. fine) in the original soil. This reconstituted approach was motivated by initial unpublished experiments on undisturbed soil samples across the region which produced highly variable results (Fennema, unpublished). Once the twenty core size fractions were split, individual reconstituted soils were thoroughly blended, placed into aluminum pie pans, and were packed to match the average bulk density. To test the effect of pre-fire soil moisture on WEP, 10 reconstituted soil cores were placed in an oven for 24 hours at 50 °C (i.e., wilting point) and 10 reconstituted soil cores were saturated until water flowed out of the bottom of the core and then drained for 24 hours (i.e., field capacity).

Similar to the litter samples, the reconstituted soil cores were prepared for laboratory fire treatment by placing 400 g m^{-2} of oven dried Western White Pine needles placed on top of the cores, following Smith et al., (2016, 2013). Before and after burning, the soil cores were weighed, and soil moisture was measured using Acclima TDR sensors. Type K thermocouples (Omega Item # TJC1-CAIN-IM025E-150) were inserted beneath the pine needles on the soil surface, in the middle of the soil core, and beneath the core. The entire sample was then placed approximately 25 cm under the SunStar Sunstar SG10 Infrared Radiant Gas Heater which ignited the pine needles. Since the focus of this experiment was to understand the effects of burning on TC, WEP, and TP, FRE treatments were held constant for all soil core treatments. FRE treatments were held constant by exposing the soil cores to the heater for the same amount of time (4.3 minutes).

After FRE treatment, the entire sample was then re-weighed, and a post burn soil moisture reading was taken. Each reconstituted soil core was re-sieved using a 1 mm screen. Sub-samples from the coarse and fine size fractions were analyzed for TC, WEP, and TP at A&L Great Lakes Laboratories. The total mass of TC, WEP, and TP was calculated for each sample by multiplying the concentration (from the laboratory analysis) by the mass of each sample.

Figure 3-2: Reconstituted Soil Core constructed to match the coarse and fine size distribution and the average bulk density from bulk density samples collected in the field. The picture in the middle shows a reconstituted soil core in the aluminum pie pan with pine needles and thermocouples inserted (wrapped in an aluminum heat shield) ready to burn. The bulk density was reproduced by packing the soil core back to the original bulk density. The picture on the right shows a sample after burning.

By taking samples before and after burning, TC and the two P pools (WEP and TP) were tracked in both the coarse and fine size fractions for each reconstituted soil core. In this experiment, the Western White pine needles (added to ensure that the soil surface is exposed to direct flame and produce a known fire radiative energy) imported additional TC, WEP, and TP to the system. Five samples of burn and unburned Western White pine needles were submitted to A&L Great Lakes Laboratories for analysis of TC, WEP, and TP.

Results were used to complete a mass balance analysis of TC, WEP, and TP in the litter and soils samples to understand the net effect of burning both the litter and the soil on P and C. The average pre-burn nutrient results in mass and concentration were used as the baseline content for the percent change analysis. The pre-burn samples included the nutrient mass added from the Western White Pine needles, the coarse and the fine mineral soil size distributions. Statistical significance was quantified using a Welch T-test (Welch, 1947).

Throughout the paper, nutrient concentration, nutrient content, and percent change are presented. Nutrient content is often expressed in terms of kg/ha for a given soil thickness (e.g., 10 cm soil horizon) or tons/ac for the top 1 ft soil thickness. In this paper, we present nutrient content in terms of mass within a specific reconstituted soil core. Percent change is calculated as a function of nutrient content change before and after burning.

Results

In total, there were 5 litter samples and 4 soil core treatments with 5 reconstituted soil core per treatment for a total of 20 soil cores. Results of the litter samples are presented first, followed by the reconstituted soil cores. Last, the mass balance results analysis is presented.

Litter Samples

The litter samples were burned until they smoldered out, which lasted ~11 minutes on average. The average maximum surface temperature reached 545 °C. The litter samples received an average of 109 kW m^{-2} of FRP and 71.1 MJ m^{-2} of FRE. Table 3-1 summarizes the FRE treatment to the litter samples.

Table 3-1: Summary of the fire radiative energy dosing (FRE) to the litter samples. The average and standard error (SE) are presented at the bottom of the table.

Sample	**Burn Time (m)**	**Maximum Surface Temp (°C)**	**Average Power (kW m^{-2})**	**FRE (MJ m^{-2})**
Litter 1	8.9	470.9	111.0	59.8
Litter 2	10.7	735.5	109.0	70.2
Litter 3	11.5	632.1	109.7	76.0
Litter 4	13.9	416.5	113.4	94.9
Litter 5	8.9	468.3	101.7	54.5
Average	10.8	544.7	109.0	71.1
SE	0.8	53.6	1.8	6.3

After burning the organic matter samples there was a significant reduction in TC content ($p = 0.059$) at an α level of 0.1 however there were no significant differences in the WEP and TP content ($p = 0.41$ and 0.44, respectively). Table 3-2 displays the pre- and post-burn and the change in TC, WEP, and TP content and concentrations. Figure 3-3 shows the TC, WEP, and TP pre-, post-burn, and percent change for each litter sample.

The TC concentration in the litter samples decreased by 67% (SE = 5.2%) after burning. The following insignificant trends were observed. WEP concentration decreased in three out of the five samples. TP concentration increased in all but one of the samples following burning. Across all samples, there was a slight increasing TP content trend following burning.

Reconstituted Soil Core: Total Carbon, Water Soluble Phosphorus, and Total Phosphorus Mass Balance Approach

Of the entire bulk soil sample, 27.4% of the total soil mass was fine (less than 1 mm), 72.4% of the sample was coarse (greater than 1 mm) and 0.2% was organic matter primarily composed of roots. The roots were removed from the analysis. A wet bulk density was determined for the five collected bulk density samples (Table 3-3). The reconstituted soil cores were constructed to match both the average bulk density and the size fraction distribution. Reconstituted soil cores were weighed before and after moisture treatments (Table 3-4). On average, the volumetric water content of the wet soil cores decreased from 8.3% (standard error = 0.42%) to 6.6% (standard error = 0.65%) moisture before and after burning, resulting in a 22% decrease in the volume of water present.

Table 3-2: Forest Floor Litter Total Carbon (TC), Water Extractable Phosphorus (WEP) and Total Phosphorus (TP) change from before and after Burning. Change is calculated as post-burn minus pre-burn values; * indicates statistical significance at α = 0.1 level and ** α = 0.05.

	Litter 1			**Litter 2**			**Litter 3**			**Litter 4**			**Litter 5**		
	Pre	**Post**	**Δ**	**Pre**	**Post**	**Δ**	**Pre**	**Post**	**Δ**	**Pre**	**Post**	**Δ**	**Pre**	**Post**	**Δ**
Total TC (g)	236	75	-162	277	127	-150	204	63	-141	374	157	-217	1,065	133	-932
Total WEP (mg)	62	14	-48	68	126	58	50	6	-44	67	12	-54	210	237	28
Total TP (mg)	1,335	965	-370	1,290	1,315	25	1,220	858	-362	1,220	1,552	332	1,030	1,992	962
Total Mass (g)	1,315	975	-340	1,563	1,277	-286	1,102	841	-261	2,258	1,764	-494	4,095	3,830	-265

	Average Pre	**SE Pre**	**Average Post**	**SE Post**	**Average Δ**
Total TC (g)	431	144	111	16	-320*
Total WEP (mg)	91	27	79	41	-12
Total TP (mg)	1,219	47	1,336	184	117
Total Mass Lost (g)	2,067	486	1,737	489	-329

	Litter 1			**Litter 2**			**Litter 3**			**Litter 4**			**Litter 5**		
	Pre	**Post**	**% Δ**	**Pre**	**Post**	**% Δ**	**Pre**	**Post**	**% Δ**	**Pre**	**Post**	**% Δ**	**Pre**	**Post**	**% Δ**
Total TC (%)	18%	8%	-10%	18%	10%	-8%	19%	7%	-11%	17%	9%	-8%	26%	3%	-23%
Total WEP (mg/kg)	48	15	-69%	43	99	128%	46	7	-85%	30	7	-76%	51	62	21%
Total TP (mg/kg)	84	99	19%	79	103	30%	72	102	42%	72	88	22%	53	52	-2%

	Average Pre	**SE Pre**	**Average Post**	**SE Post**	**Average Δ**
Total TC (%)	19%	2%	7%	1%	-12%**
Total WEP (mg/kg)	43	3	38	16	-16%
Total TP (mg/kg)	719	47	888	86	22%

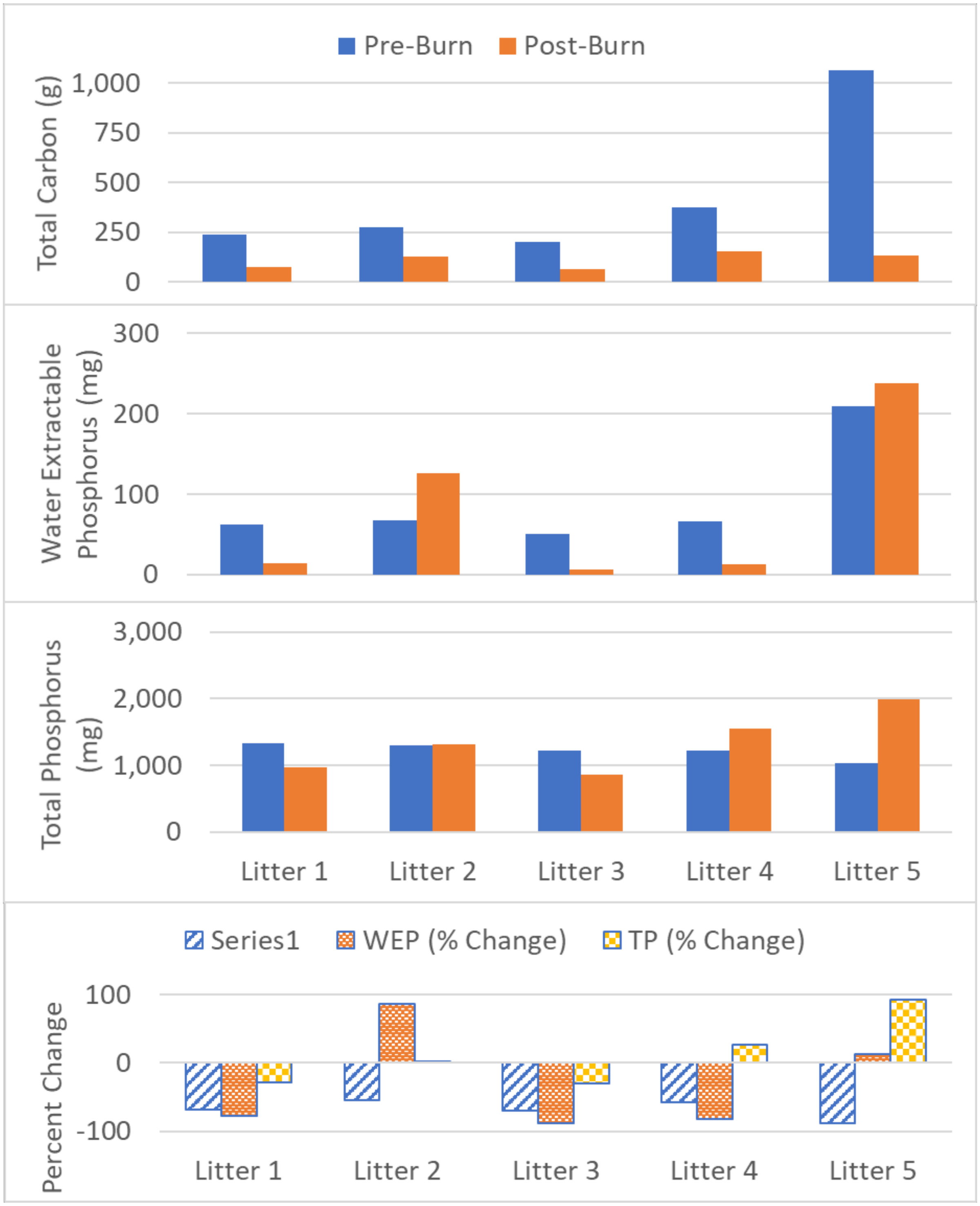

Figure 3-3: Forest Floor Litter Pre-Burning constituent mass (in blue), post-burning constituent mass (in red). The top plot shows Total Carbon mass per sample. The second plot from the top shows Water Soluble Phosphorus mass per sample, and the third plot down plot shows Total Phosphorus. The last plot shows the percent change in TC, WEP, and TP before and after burning for each of the litter samples.

Table 3-3: Wet bulk density sampling results

Bulk Density ID	Soil Mass (g)	Bulk Density (g/cm^3)
BD-1	119.1	1.32
BD-2	117.4	1.30
BD-3	121.9	1.35
BD-4	112.4	1.24
BD-5	118.1	1.31
	Average Bulk Density	1.30

Table 3-4: Wet and dry reconstituted soil core average mass and volumetric water content before and after treatments

Treatment	Pre-Treatment		Post-Treatment			
	Average Mass (g)	Average Volumetric Water Content (%)	Average Mass (g)	Average Volumetric Water Content (%)	Average Mass Loss (g)	Average Volumetric Water Content Loss (%)
Dry Treatment	2,145	0%	2,032	0%	-13	0%
Wet Treatment	2,168	8.3%	2,293	6.6%	-44	-21.9%

The pine needles had the highest concentration of TC, WEP, and TP; however, only 400 g/m^2, or 13 grams of pine needles, were placed on each reconstituted soil core, and added a relatively small amount nutrient content to the overall sample mass. Table 3-6 shows the average content and Table 3-7 shows the average concentration of TC, WEP, and TP and SE from the pre-burn sample analysis.

Soil cores were exposed to the heater and burned for 4.3 minutes on average. Surface temperatures were measured throughout the FRE treatments in the dry samples and averaged 475 °C. FRE was held constant at average of 28.75 MJ m^{-2} (SE = 0.37 MJ m^{-2}).

Table 3-5: Summary of the fire radiative power (FRP) and fire radiative energy (FRE) applied to the reconstituted soil core samples.

Sample	**Burn Time (mins)**	**Max FRP ($kW m^{-2}$)**	**FRE ($MJ m^{-2}$)**
AD 1	4.26	109	28.0
AD 2	4.34	114	29.4
AD 3	4.21	115	29.3
AD 4	4.26	107	27.7
AD 5	4.33	110	28.3
AD 6	4.29	119	30.5
AD 7	4.27	125	32.1
AD 8	4.27	99	25.6
AD 9	4.3	105	27.1
AD 10	4.28	107	27.6
AW 1	4.22	113	28.8
AW 2	4.13	113	28.3
AW 3	4.22	106	27.1
AW 4	4.24	115	29.4
AW 5	4.26	110	28.3
AW 6	4.38	110	28.3
AW 7	4.21	109	27.8
AW 8	4.28	111	28.5
AW 9	4.38	129	33.1
AW 10	4.3	115	29.6
Average	4.27	111.97	28.75
SE	0.06	2.21	0.37

After burning the reconstituted soil core samples were re-sieved into the coarse and fine sizes; the pine needle ash was incorporated into different size fractions. Table 3-6 and Table 3-7 shows the average content and concentration of TC, WEP, and TP and SE from the pre- and post-burn sample analysis. The dry fine (AD Fine) size fraction contained the highest constituent content across the board after burning. The average TC content (p-value 2.62 x 10^{-5}) and concentration (p-value 5.97 x 10^{-5}) across the wet and dry soil cores significantly decreased following burning in comparison to the pre-burn samples. Average WEP content decreased significantly (p-value 5.00 x 10^{-5}) in the wet and dry samples combined. However, the WEP concentration increased in the dry samples (p-value 6.13 x 10^{-3}) and decreased in the wet samples but the increase was not significant (p-value 0.32). TP content also decreased, and the concentration increased. TP changes were not significant (p-value 0.19 for content and 0.53 for concentration). Table 3-6 and Table 3-7 show the content and concentration results. Figure 3-4 shows the TC, WEP, and TP content by component (coarse and fine size fraction, and the pine needles added to the surface).

Table 3-6 Pre- and post-burn sample average content and standard error (SE) from the total carbon (TC), water extractable phosphorus (WEP), and total phosphorus (TP) analysis for the wet (AW) and dry (AD) samples at the coarse and fine size fractions in terms of constituent concentration.

Samples	**Coarse TC (g)**		**Fine TC (g)**		**Pine Needle TC (g)**		**Total TC (g)**		**Average Δ TC (g)**	**P-Value**
	Average	**SE**	**Average**	**SE**	**Average**	**SE**	**Average**	**SE**		
Pre-Burn	25.9	1.6	20.4	0.3	6.7	0.03	53.0	1.5	-	-
AD	14.3	1.1	19.2	0.5	-	-	33.5	1.5	-19.6	4.72E-06
AW	19.2	1.0	19.6	0.4	-	-	38.8	1.2	-14.2	1.01E-04

Samples	**Coarse WEP (mg)**		**Fine WEP (mg)**		**Pine Needle WEP (mg)**		**Total WEP (mg)**		**Average Δ WEP (mg)**	**P-Value**
	Average	**SE**	**Average**	**SE**	**Average**	**SE**	**Average**	**SE**		
Pre-Burn	6.4	1.6	5.2	0.2	4.1	0.0	15.7	0.6	-	-
AD	6.8	1.1	3.6	0.5	-	-	10.5	0.3	-5.21	4.54E-04
AW	6.1	1.0	1.7	0.4	-	-	7.8	0.3	-7.88	2.35E-05

Samples	**Coarse TP (mg)**		**Fine TP (mg)**		**Pine Needle TP (mg)**		**Total TP (mg)**		**Average Δ TP (mg)**	**P-Value**
	Average	**SE**	**Average**	**SE**	**Average**	**SE**	**Average**	**SE**		
Pre-Burn	701.1	1.6	329.9	0.2	6.5	0.0	1037.6	8.3	-	-
AD	694.2	1.1	327.3	0.5	-	-	1021.5	26.6	-16.1	5.98E-01
AW	675.7	1.0	321.6	0.4	-	-	997.3	24.8	-40.3	1.74E-01

Table 3-7: Pre- and post-burn sample average concentration and standard error (SE) from the total carbon (TC), water extractable phosphorus (WEP), and total phosphorus (TP) analysis for the wet (AW) and dry (AD) samples at the coarse and fine size fractions in terms of constituent concentration.

	Coarse TC %		**Fine TC %**		**Pine Needle TC %**		**Total TC %**		**TC Percent Change**	
	Average	**SE**	**Average**	**SE**	**Average**	**SE**	**Average**	**SE**	**Average**	**P-Value**
Pre-Burn	1.7%	0.1%	3.5%	0.0%	51.3%	0.2%	2.4%	0.1%	-	-
AD	0.9%	0.1%	3.3%	0.0%	-	-	1.6%	0.0%	-0.9%	1.98E-05
AW	1.2%	0.1%	3.3%	0.0%	-	-	1.8%	0.0%	-0.7%	1.24E-04

	Coarse WEP (mg/kg)		**Fine WEP (mg/kg)**		**Pine Needle WEP (mg/kg)**		**Total WEP (mg/kg)**		**WEP Percent Change**	
	Average	**SE**	**Average**	**SE**	**Average**	**SE**	**Average**	**SE**	**Average**	**P-Value**
Pre-Burn	4.1	0.3	3.3	0.3	316.4	0.0	3.9	0.2	-	-
AD	4.4	0.2	6.2	0.3	-	-	4.9	0.1	26%	6.16E-03
AW	3.9	0.2	2.8	0.1	-	-	3.6	0.1	-7%	3.24E-01

	Coarse TP (mg/kg)		**Fine TP (mg/kg)**		**Pine Needle TP (mg/kg)**		**Total TP (mg/kg)**		**TP Percent Change**	
	Average	**SE**	**Average**	**SE**	**Average**	**SE**	**Average**	**SE**	**Average**	**P-Value**
Pre-Burn	448.0	5.9	558.0	1.8	500.0	0.0	460.1	9.4	-	-
AD	446.0	6.0	555.0	7.0	-	-	476.0	4.3	3%	2.18E-01
AW	429.2	7.1	539.0	8.5	-	-	459.4	6.5	0%	9.59E-01

Mass Balance Nutrient Approach

The TC, WEP, and TP content of the reconstituted soil cores with the added Western white pine needles changed after burning. Post-burn TC content was 37% (19 g) lower in the dry samples and 27% (14 g) lower in the wet samples than pre-burn levels, see Figure 3-5. WEP content significantly (p-value 5.0×10^{-5}) decreased by an average of 42% in both treatments combined. In the dry samples, WEP decreased by 33% (5 mg; $p = 4.5 \times 10^{-4}$) on average and by 50% (7.9 mg; $p = 2.35 \times 10^{-5}$) on average in wet samples. TP content generally decreased across all treatments, but the results were not significant ($p = 0.6$ for the dry samples and 0.17 for the wet samples). In 5 of the 20 samples, TP increased. Figure 3-4 shows the individual soil core results for TC, WEP, and TP. Figure 3-5 show the percent change each in TC, WEP, and TP content core experienced before and after burning.

Although the decreases in TC and WEP content were statistically significant before and after burning, the magnitude of these changes were correlated to the initial soil moisture content. TC experienced less loss when the initial soil moisture content was higher before burning. This finding was significant (p-value 2.55×10^{-9}). In contrast, WEP loss increased when initial soil moisture was higher (p-value 7.44×10^{-11}). TP changes before and after fire were not significant, and therefore not compared to soil moisture.

Change between the wet and dry post-burn results were also compared to determine statistical significance. TC and WEP post-burn changes were significant between the wet and dry samples (p-value 1.49×10^{-3} and p-value 5.47×10^{-4}, respectively). TP changes between the wet and dry samples were not significant. Table 3-8 presents the pre-burn nutrient contents as well as the changes and significance comparison between wet and dry post-burn treatments.

Table 3-8: Comparison of the Post-Burn Constituent Change between the Wet and Dry Samples

	TC	WEP	TP
Pre-Burn Average Nutrient Content (TC in g; WEP and TP in mg)	53.0	15.7	1,038
Wet Average Nutrient Content Loss (TC in g; WEP and TP in mg)	-14.2	-7.9	-40
Dry Average Nutrient Content Loss (TC in g; WEP and TP in mg)	-19.6	-5.2	-16
P-Value Comparison of Wet and Dry Post-Burn Results	1.49E-03	5.47E-04	0.28

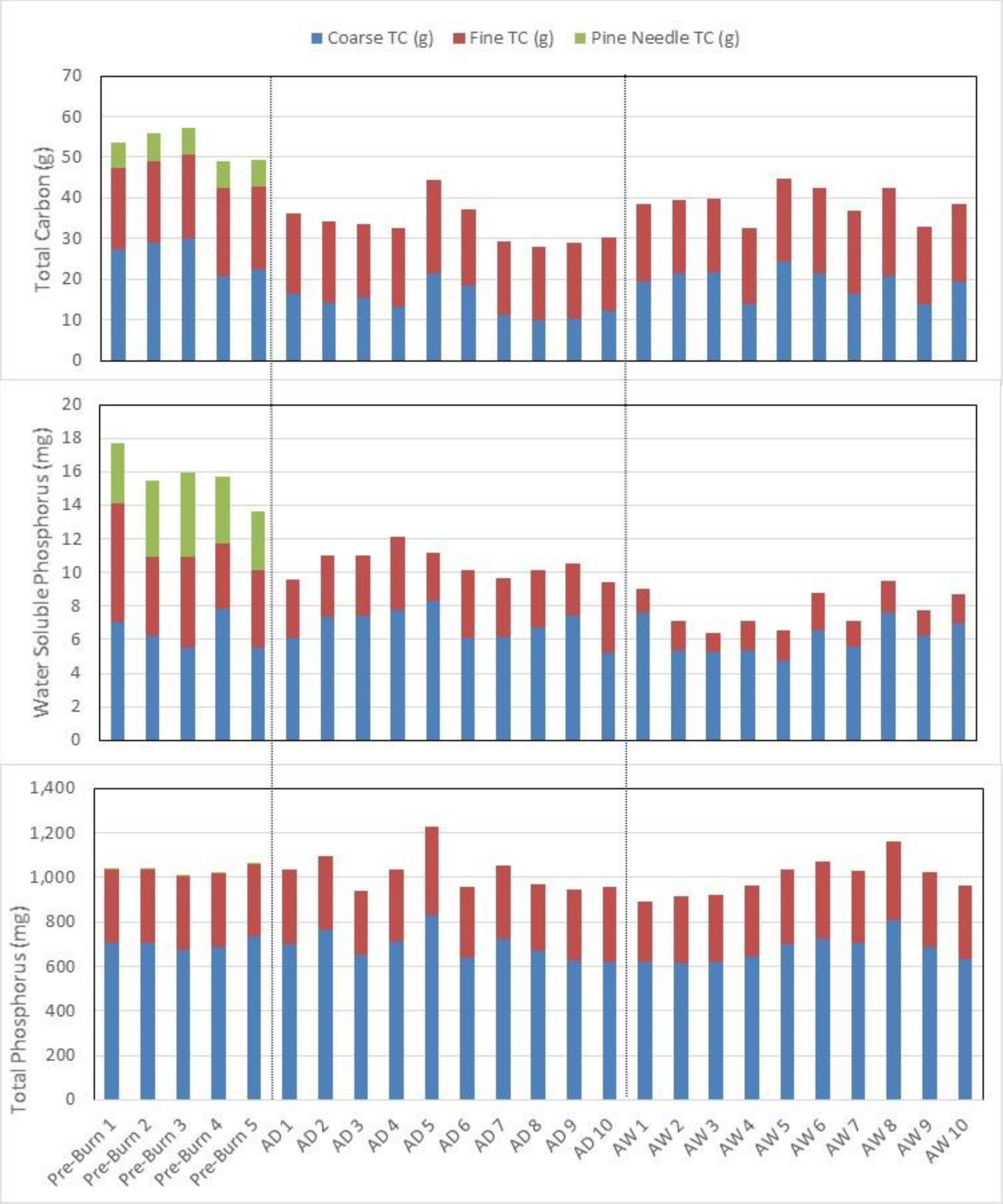

Figure 3-4: Results for the individual sample nutrient analysis. The top plot shows total carbon mass in each sample in grams. The middle plot shows the mass of water extractable phosphorus in mg. The bottom plot shows the total phosphorus mass in mg. The fine size fraction is in red and the coarse in blue. The pre-burn (dosing) samples also include the results of the pine needle (shown in green) nutrient mass added into the system.

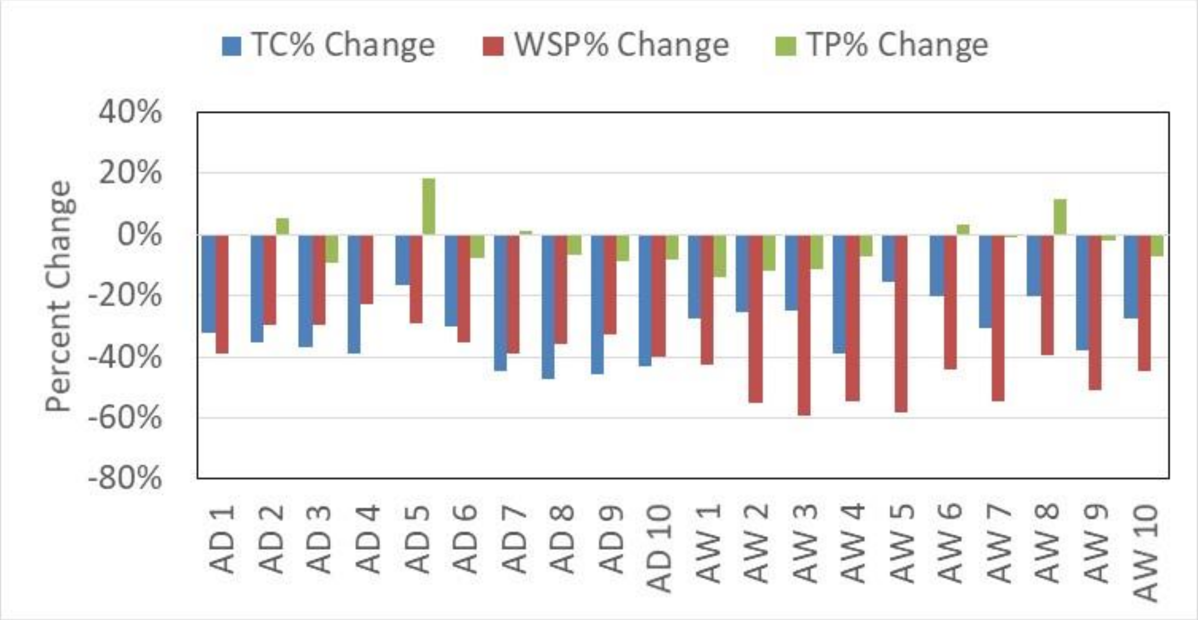

Figure 3-3: The plot shows the percent change of nutrient concentrations from before to after moisture and burning treatments. Average pre-burn nutrient concentrations were used as the baseline pre-burn conditions. Total carbon (TC) is shown in blue, water soluble phosphorus (WEP) is in red, and total phosphorus (TP) is in green.

Discussion

Litter Samples

Impacts of wildfire on TC, WEP, and TP within the forest litter or duff layer were highly variable with few consistent trends. TC content and concentration decreased in all the samples following the FRE treatment. However, the range of decrease was large between each sample. The decrease in TC content is in similar magnitude to previous field studies that have noted TC decrease following fires (Beringer et al., 1995). Previous lab studies using muffled furnaces have shown no change to TC (Lombao et al., 2015) or slight decreases when temperatures are above 500 °C (Glass et al., 2008). Soil heating in muffled furnace, however, do not allow for direct flame contact (Stoof et al. 2010). The TC differences between muffled furnace literature and our results may be explained by the lack of combustion in muffled furnaces.

WEP content and concentration dropped on average across all the samples but the results varied largely between each sample. Portions of the partially burned TC would most likely convert to black carbon (Czimczik et al., 2003; González-Pérez et al., 2004). WEP is highly reactive (Froelich, 1988; Smith et al., 2005) and is likely binding to the black carbon.

TP content and concentration increased following the litter burning. WEP binding to active sites on the black carbon may explain the WEP decreases and the increases in TP. However, the magnitude of TP was much greater than the WEP decrease observed. This indicates that the increase in TP is being released from some other sources within the litter following fire.

Reconstituted Soil Cores

In the literature, post-fire WEP concentrations have been known to increase following fire (e.g., Lynham et al., 1998; Cade-Menun et al., 2000; Johnson et al. 2014). Many researchers have also noted increases in biological available P (e.g., orthrophosphorus, soluble reactive P) following fire on hillslopes (Miller et al. 2008; Johnson et al. 2014) and in streams below fires (Oliver et al., 2012). Increases in Bray extractable P have been noted 10 years after a fire in soils with granitic parent material (Lynham et al., 1998). 60 years after a fire, Johnson et al., (2012) observed a significant decrease in Bray extractable P in andic soils and an insignificant decrease in granitic; Johnson el al., (2012) noted the importance of soil parent material in long-term P changes.

In this experiment, WEP content and concentration decreased in the mineral soil, while the change in WEP in the litter varied wildly. In this experiment, we separated the duff from the mineral soil to identify P shifts in each component (i.e., litter, coarse and fine mineral soil). WEP content decreased in the mineral soil following burning, which conflicts with previous studies. The difference we observed may be caused by the separation of the litter from the mineral soil. This possibility is further discussed below. Additionally, this experiment focused on quantifying the nutrient changes in a single homogenized soil sample, which further reduced the natural variation of soils within a watershed.

FRE treatments had little to no effect on TP content in the mineral soils, matching previous work (Cade-Menun et al., 2000). In 15 out of the 20 samples TP decreased by 6% on average and increased in 5 of the samples by 8%. Johnson et al., (2014) found that TP decreased in soils following thinning and a prescribed burn by approximately 20%, however the findings were not significant. Whereas Cade-menun et al., (2000) found TP concentrations did not change following a prescribed burn, but noted that there was a shift from organic to inorganic, mineralized P forms. Downslope of the Angora Fire (Oliver et al., 2012), TP loading increases were larger the second year following the wildfire, which was, also, much wetter than the first. TP loading is directly related to postfire erosion rates compared to the TP concentration and content present in the soil.

Average TC was reduced by 27% in the wet samples compared to 37% in the dry samples. Many studies have noted decreases in TC following fire (Johnson et al., 2014; Cade-Menun et al., 2000). However, previous studies have not quantified the difference in TC reduction following fire in wet and dry conditions. The increase soil moisture may have prevented TC from fully volatilizing, charring organic material and increasing the black carbon present (Gonzalez-Perez et al., 2004). The TC decreases match our hypothesis that soil moisture would absorb the latent heat added by the FRE and retard changes nutrient changes.

In contrast TC, WEP decreases were larger in the wet mineral soil cores. WEP decreases were larger in the wet samples (50% reduction on average) compared to the dry samples (33% reduction). Our hypothesis for this experiment was that increased soil moisture would absorb the latent heat added by the FRE and retard changes in TC, WEP, and TP. Soil moisture did affect the nutrient changes after exposure to FRE but not in the way that we hypothesized.

Conceptual Model of Wildfire Effects on Phosphorus Availability and Transport

The experimental design in this project allows us to take a more comprehensive look at the impacts of wildfire on the P concentrations and content of each of the soil components. If the litter were to have remained on the soil, following burning the litter ash residue would have integrated into the soil surface or been eroded away if not protected from rainfall/runoff. The surface of the mineral soil would have formed an ash-mineral soil blend, which would change the interaction of TC, WEP and TP.

During the FRE experiment the litter lost 75% and the mineral soil lost 36% of its TC. The average post fire residual had 9 Mg ha^{-1} TC in the litter and 16 Mg ha^{-1} in the mineral post-fire. The net effect of burning is an overall decrease in TC if the soil components were burned intact (i.e., the litter remained on the soils when burned). However a portion of the TC would convert to the highly reactive black carbon (Czimczik et al., 2003; González-Pérez et al., 2004) and become part of the mineral soil.

WEP concentration and content decreased in the duff and wet soil samples. Concentration of WEP increased in the dry mineral samples. Overall, there would be a net decrease in WEP if the litter had not been removed from the soil. We speculate that the additional TC from the litter would likely add more black carbon to the in the ash-mineral soil blend and may further reduce the WEP content and concentration in the mineral soil.

Had the litter and the mineral soil not been separated, the increase in TP concentration from the litter would have integrated on the surface into the ash-mineral soil blend. The mineral soil did not experience significant shifts in TP post fire. The net effect would result in an increase in the TP in the ash-mineral soil blend. Since the TP content did not increase, the TP concentration rise is most likely from the fire burning off other material and concentrating the TP into the ash-mineral soil blend. The surface ash-mineral soil layer would also be susceptible to soil erosion if not incorporated into the mineral soil following some sort of revegetation or stabilization. As TP concentrates there is a greater risk of increased phosphorus loading from the watershed, which could impact downstream water quality especially as fires are increasing in intensity and frequency.

TC and WEP concentrations decreased in the duff layer samples; however, the total mass of duff decreased post-burn—further concentrating the nutrients in the shallow near surface soil. Previous research showed an increase in TP (Oliver et al., 2012) and biologically available P mobility following high severity wildfires in surface runoff (Miller et al., 2008) and streamflow (Oliver et al., 2012); both of these papers noted post-fire hydrophobic condition. Hydrophobic soils reduce the infiltration capacity of the soils and increase the amount of runoff through the shallow near surface soils where the burned litter material would reside. Increased runoff through the burned litter and concentrated mineral soil would increase the risk of downstream nutrient loading.

Management Implications

Forest fires have been increasing in both intensity and frequency (A. L. Westerling et al., 2006). Post-fire erosion rates can increase by orders of magnitude (Elliot et al., 2006), carrying critical limiting nutrients, such as P, and impacting downstream water quality (Wondzell and King, 2003). In forested, alpine systems many lakes are P limited (e.g., Goldman, 1988; Kootenai Environmental Alliance, 2012; La Croix and Wilhelm, 2016; Woods and Beckworth, 1997). Forest management practices affect downstream water quality. WEP can easily be dissolved and transported following rainstorms or periods of snowmelt. Dissolved P is a biological available form of P that can lead to increased algae productivity within alpine, oligotrophic lakes. This research found that wet soils retained more soil TC and experienced larger decreases in WEP concentration and content following simulated wildfire. We speculate that black carbon concentrations increased following burning which then further reduced the WEP by adsorbed. Reducing WEP in soils will reduce dissolved P loading. Implementing control burns while the soil is wet may lead to larger decreases in WEP and reduced impact on downstream water quality.

Conclusions

Forest management practices can directly impact downstream water quality. Previous studies have quantified the impact of forest fire and prescribed burns on soil nitrogen and carbon. In this lab-based experiment using a radiant heater to control the amount of Fire Radiative Energy exposed to reconstituted soil core, we quantified the shifts in soil phosphorus from an andic soil from the Pacific Northwest to quantify shifts in TC, WEP, and TP before and after a simulated forest fire. We specifically designed the experiment to separate out the impacts of wildfire on TC, TP, and WEP in the organic duff layer and the mineral soil. We observed significant losses of carbon following burning from duff layers with no significant losses of total phosphorus content. Similar trends were observed in the mineral soils. Results indicate that burning wet soils reduces the amount of TC loss. Interestingly, WEP content decreased more in the wet soils and increased in the dry soils. We speculate that the greater residual black carbon in the wet soils is binding phosphorus more strongly which is leading to a reduced WEP. Since fire does not impact TP and with the loss of overall biomass and carbon, we conclude that the TP concentration increases. With an increase in TP concentration and a much greater risk of erosion following wildfire in forested landscapes leaves the landscape at a high risk for particulate P transport to downstream water bodies. With the increased WEP in dry soils and the increased risk of runoff from hydrophobic soils following wildfire suggests that under dry wildfire dissolved P loading will also increase. In contrast these results suggest that a prescribed burn under wet soil conditions will reduce WEP and likely reduce dissolved P loading to downstream water bodies in streams

This study used a single homogenized andic soil sample to reduce the heterogeneity of the results. As such, the natural variability in watershed soils was not captured. Previous field studies on granitic parent material soils (e.g., Miller et al., 2008; Oliver et al., 2012) responded differently than the results found in this study. Soil P availability changes based upon the soils parent material (Johnson et al., 2012; Heron et al. 2021). Therefore, we recommend repeating this experiment using more soil types to understand soil P dynamics in other soils of varying parent material.

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Chapter 4: Integrating Cultural Perspectives into International Interdisciplinary Work[1]

Abstract

There are well-established methods for working in interdisciplinary natural resource management settings, but place-based cultural differences are often poorly integrated into interdisciplinary projects. Intercultural adequacy is necessary to ensure that water management strategies are acceptable within the local contexts of water users. In this study we followed four cohorts of graduate students from Canada, Chile, Cuba, and the United States that participated in an international graduate-level water resource management course hosted at the Universidad de Concepción in Chile. The North American students participated in post-experience surveys and interviews to assess changes in their interdisciplinary and intercultural comfort levels. The interviews and survey identified factors that enhanced or detracted from their progress towards integrating disciplinary and cultural differences into their work. Though course material promoted interdisciplinary collaborations across various disciplinary cultures, participants noted that traditional methods of integrating did not adequately bridge differences in place-based cultural worldviews. We propose a framework developed during the experience to integrate place-based cultural differences into all phases of the interdisciplinary research and natural resource management processes.

Introduction

Water resource management impacts natural, social, and economic systems. Water managers must consider impacts on all systems (Grigg 2016) through interdisciplinary lenses. Applying an interdisciplinary approach in water resource management allows for the incorporation of different disciplinary viewpoints and understandings to develop concrete management solutions to specific problems. Working in interdisciplinary groups poses many challenges, however. Disciplinary language barriers disrupt communication (Cosens et al. 2011; Repko 2012). Disciplinary methodologies vary (Repko 2012), which can be frustrating and often culminates in a lack of trust between disciplines and research group members (Heemskerk et al. 2003; Eigenbrode et al. 2007; Cosens et al. 2011).

The interdisciplinary literature has established methods to create a synthesis of understanding by weaving together relevant disciplinary knowledge (Newell 2001; Cosens et al. 2011). The process aides in understanding complex problems in natural sciences, social sciences, and the humanities

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(Newell 2001). We propose fostering intercultural adequacy by adding culturally focused discussions into interdisciplinary methodology. We define intercultural adequacy as the process of integrating place-based cultural views, discussions, and understanding into the interdisciplinary process so that individuals can work across cultural differences. Intercultural adequacy incorporates cultural contexts into natural resource research and management. The term intercultural adequacy mirrors interdisciplinary adequacy, where Cosens et al. (2011) recognize that it is highly unlikely for individuals to become experts in more than one discipline—or in the present context, for cultural learning to translate into competency (Zotzmann 2016).

We follow the method of interdisciplinary investigations and integration presented by Cosens et al. (2011), which begins by building disciplinary adequacy from each represented field to overcome disciplinary barriers (Cosens et al. 2011; Repko 2012). Disciplinary adequacy requires building a basic understanding of the methodologies, assumptions, and terminology from the various disciplines represented on the interdisciplinary team. With an understanding of the differing disciplines, the interdisciplinary team can foster disciplinary trust through interactive exercises such as the *Toolbox for Philosophical Dialogue* (Toolbox; Eigenbrode et al. 2007). The Toolbox is a series of prompts that facilitates dialogue to identify and address philosophical differences and similarities among disciplines from biological to physical to social sciences. Conceptual models or diagrams then can be constructed to aid interdisciplinary teams to create a simplified representation of the system of study (Heemskerk et al. 2003). The conceptual model can serve as a platform to develop complex integrating questions (Thompson Klein 1991; Newell 2001; Cosens et al. 2011) that cannot be answered using a single discipline approach (Thompson Klein 1991; Newell 2001; Cosens et al. 2011). Developing an integrating question and designing a conceptual model allowed team members to narrow the scope of their project, create a communication platform for ideas (Heemskerk et al. 2003), and continually check the focus of their working hypotheses. Figure 4-1 presents a flow chart of this interdisciplinary process.

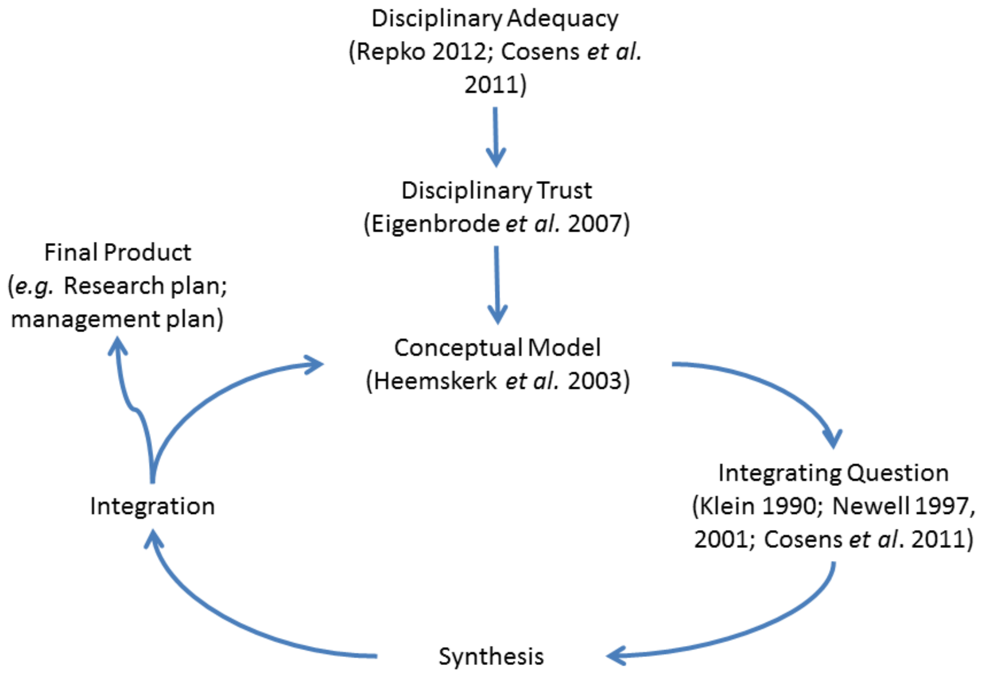

Figure 4-1: Overview of the Interdisciplinary Process Presented in Cosens et al (2011).

Working in an interdisciplinary space also requires intercultural awareness (Muratovski 2017; Thompson Klein et al. 2018) and intercultural competency (Sarmento 2016). In 2018, the Association for Integrative Studies expanded its mission statement to explicitly include cultural diversity as an integral component of interdisciplinarity (Thompson Klein et al. 2018). Currently, there is multiplicity in definitions of intercultural study in the interdisciplinary literature. In some cases, the interdisciplinary literature focuses on differences between disciplinary cultures (Reich and Reich 2006; Thompson Klein et al. 2018)—even with relatively narrow differences such as between the humanities and the arts (Lotrecchiano and Hess 2019). Other articles stress the need for understanding place-based cultures and practices (e.g., Egidiussen Egekvist et al. 2016) and integrating culturally based ways of knowing into research designs (Morgan 2006; Sterling et al. 2017). The movement of adding intercultural discussions into the interdisciplinary process is still relatively new. Literature about interdisciplinary studies and intercultural studies remains largely separated.

Disciplinary and place-based culture are defined differently. Disciplinary culture is the difference between the norms and practices of one discipline versus another within the academic community (Reich and Reich 2006). Place-based culture is defined as beliefs, customs, lifestyles, and arts of a particular society or group. Place-based culture is often tied in place and time to landscapes themselves, and must be interpreted in relation to context, history, and power (Swensen et al. 2013).

Natural, family, and social experiences may additionally be incorporated into an individual's cultural worldviews.

Understanding and acceptance of cultural differences is a process. Responses to exposure to other cultures can be described on a continuum, where individuals may begin with denial, defense, and minimization of other cultures—especially if the cultural differences are overwhelming (Hammer 2012)—before accepting or adapting to the foreign culture (Figure 4-2). Individual or group development across the continuum to an intercultural mindset, or open acceptance of cultural differences, is aided by supportive interactions with people from different cultures (Hammer 2012). Hammer and Bennett (1998) propose an Intercultural Development Index (IDI) that is often used to assess the progress towards the intercultural sensitivity of students in international immersion experiences. In the interdisciplinary, intercultural context, individuals need to move across the cultural continuum for each of the cultural differences faced, such as disciplinary and place-based cultural differences.

Specific methodologies can further close the gap between disciplinary cultures by facilitating the establishment of trust within interdisciplinary teams. Existing tools do not address differences in place-based cultures, however. Allen et al. (2014) note that interdisciplinary initiatives commonly fail because of a lack of a methodology that fosters internal group dynamics and allows for group engagement and social learning. Graduate fellows in an interdisciplinary program between the United States and Costa Rica (NSF Award Number 0903479, 2012-2019) found that the lack of method(s) to integrate both disciplinary culture and place-based culture into the research process hindered team progress (Morse et al. 2007; J.D. Wulfhorst, personal communications, 5-Jan-2017).

One proposed path to bridge cultural differences and foster cultural understanding is to encourage diverse forms of intercultural dialogue and engagement (Crossley 2008; Jackson 2009). Outcomes should lead to useful integration of cultural differences and commonalities to allow for the development of shared visions, goals, or directions (Crossley 2008; Smit and Tremethick 2013; Wiek et al. 2013), now known as intercultural competence (Sample 2013). Given the term's complexity, however, there is a lack of consensus in how to operationalize intercultural competency (Wahyudi 2016). Furthermore, Zotzmann (2016) questions whether it is, "theoretically sensible and ethically desirable to conceptualize the outcomes of intercultural learning as 'competence'" (p. 252). In this manuscript, we therefore prefer the term intercultural adequacy, which parallels interdisciplinary adequacy in interdisciplinary literature (e.g., Cosens et al. 2011).

As part of an Integrative Graduate Education and Research Traineeship (IGERT) fellowship program at the University of Idaho (NSF award #1249400), graduate students participated in an interdisciplinary/intercultural experience in Concepcion, Chile. The course was listed as WR 604: Int'l Water Issues; we refer to it hereafter as the Water Issues course. Graduate students came from engineering, natural sciences, social sciences, and law backgrounds from Canada, Chile, Cuba, and the United States. Students were assigned into groups of intentionally diverse disciplinary and cultural compositions. Teams were tasked with developing a water resource management plan for the Río Laja and Río Biobío systems. After the course, North American students were interviewed and completed a survey to assess whether the course changed the participants' perceived comfort working in interdisciplinary and intercultural settings. Analysis of the interviews and surveys identified factors that helped or hindered working across cultural and disciplinary bounds.

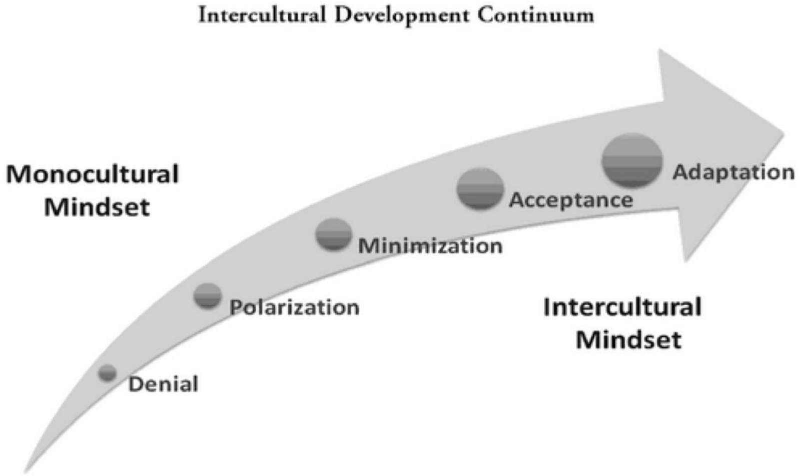

Figure 4-2: Growth from a monocultural to an intercultural mindset follows a continuum through Bennett's (1993) steps of denial, polarization, minimization, acceptance, and adaption. Integration is the ideal that lies beyond adaptation. Source: Hammer 2012.

Whether talking about disciplinary or placed-based culture, there is no clear path in the literature to include cultural discussions in the interdisciplinary process. The objective of this paper is twofold. First, we present factors that helped or hindered working in an interdisciplinary/intercultural setting; then we propose an addition to the interdisciplinary process that facilitates intercultural adequacy and cultural integration within natural and water resource management and research.

Methods

Course Context and Research Setting

The Water Issues course curriculum was taught in collaboration with Universidad de Concepción and Universidad Católica de la Santísima Concepción. The approximately three-week course was designed to integrate graduate students from various disciplinary and cultural backgrounds—law, social science, natural science, and engineering—to take part in this unique interdisciplinary experience aimed at understanding different perspectives on watersheds and watershed management. The course was offered during winter break in four consecutive academic years from 2014 to 2018. The course was divided into three dimensions: field trips, lectures, and teamwork—the proportion of time spent in each facet of the course varied year to year.

Students participated in a tour (field trip) of the Río Biobío and Río Laja Basins from the mouth of the river into the Pacific Ocean to the headwaters of both river systems. The field trip, which lasted three days on average, provided background information on the physical, geographical, and cultural settings. Time was spent with Indigenous members in Pehuenche communities, and on their lands. The field experience familiarized participants with the complexities of the Río Biobío and Río Laja Basins systems and provided social time to foster teamwork.

A week of lectures provided historical, ecological, and hydrological context, an overview of Chilean water policy and management, and regional political issues of the Río Biobío and Río Laja. Professors from the corresponding universities lectured to provide “disciplinary adequacy”—a basic understanding of the methodologies, assumptions, and terminology from each discipline (Cosens et al. 2011)—within the context of the Río Laja and Río Biobío systems. Question and answer sessions following the disciplinary lectures further facilitated cross-disciplinary communication. The lectures and question sessions were intentionally structured to allow students to understand better the importance of the current state of the watersheds, as well as the active research within each basin. The course delved into the complexities of the interdisciplinary process by presenting complex experiential case studies that link multiple disciplines.

Students were divided into working groups by the faculty, who intentionally populated each research team with diverse disciplinary and cultural representation. All groups had at least one student who could speak both English and Spanish and served as a group translator. Groups were tasked with developing water resource management plans to increase the ecological and water yield sustainability of the systems. In the context of this course, sustainability was never defined. Each team had to work out what they meant by sustainability across their disciplinary understanding. Plans were required to integrate engineering, ecological, legal, and operational recommendations. The professors leading the course allowed the students to find their own paths to accomplish the course project. However, professors encouraged students to work through the interdisciplinary process outlined in Cosens et al. (2011) (Figure 4-1) before attempting the interdisciplinary integration activities. Each group had to develop a presentation and a final report that was co-authored and co-presented by all students in the team. This paper focuses on the intercultural dynamics of the collaboration processes rather than the products from the course.

To facilitate disciplinary trust, student groups participated in a modified version of the Toolbox exercise. The Toolbox prompts were translated into Spanish for the Water Issues course, so that Spanish-speaking students could engage in the exercise in their native language, understanding, and perspectives. The Toolbox exercise allowed for team members to see behind the curtain of other disciplinary cultures by discussing the fundamental principles and assumptions used in each field through guided dialogue—taking students beyond disciplinary adequacy, developing disciplinary trust, following the interdisciplinary collaboration process. Groups were encouraged to develop a conceptual model and an integrating question to focus the team efforts to improve the sustainability of the river systems.

Data Collection: Surveys and Interviews

Following participation in the Water Issues course, the North American students from the four successive cohorts were asked to participate in a post-course survey and interview. Participation in this study was entirely voluntary, and no compensation was provided. Twenty-three out of twenty-five North American students who completed the course participated in the survey. Twenty-two of these were IGERT fellows, one of whom was a fellow in a similar IGERT program at another university. One student was from a university in Canada. We were unable to survey and interview the South American students due to institutional hurdles and lack of financial support—this is a limitation to our study since we were only able evaluate insights from the North American half of the student cohorts. We do, however, include in our results some observations that our Chilean colleagues offered during and after the experience.

The survey and semi-structured interview format were designed using Hammer and Bennett’s (1998) IDI. Questions were organized into three categories following Medina-López-Portillo (2004): individual student experience, external course dynamics, and student decisions. Individual student experience questions built an understanding of participants’ previous years in interdisciplinary work, immersion experiences abroad, proficiency in other languages, and personal experiences in the course. External course dynamics questions were designed to get the participants' viewpoints on the content provided by the organizers and instructors in the Water Issues course. External course dynamics factors included pre-trip orientation, lecture topics, and the amount of time spent in classroom lectures and field trips. The third section was focused on understanding choices made by students during the course, such as the extent of contact and immersion efforts with their international colleagues.

The survey component collected background information using quantitative Likert-scaled responses via the online Qualtrics™ survey platform. Potential identifiers were removed, and respondents were randomly assigned an identification number to preserve confidentiality. The survey instrument proved useful by collecting data for quantitative analysis. Participants were asked to complete the survey instrument before their interviews.

Interviews followed the developmental interview process described by Hammer (2012), which leads to more robust survey data in the IDI context. The core intent of the semi-structured interviews was to explore students' collaborative experiences to learn how they negotiated disciplinary and place-based cultural differences in their team science efforts. Students were asked to provide details of specific incidents of cultural differences that impacted the group project, how they navigated the situation, and their perceived outcomes (Hammer 2012). By asking similar questions in multiple forms, the combination of surveys and interviews allowed for triangulation (i.e., asking similar questions from different angles) of responses to cross-check for consistency.

One researcher conducted all interviews. The interview duration averaged 30 minutes with a minimum and maximum of 20 and 33 minutes, respectively. Interviews were administered in person, by phone, or by video conferencing, and were recorded. One participant responded to the questions in writing from a remote location. Additional interview questions emerged during the first few conversations and were carried forward through subsequent interviews. Transcripts of responses were coded into an expanded matrix of questions. Direct references to other members of the cohorts were removed to preserve confidentiality. Respondents' names were replaced by matching identification numbers on interviews and surveys. Statements were aggregated by question to discover trends in responses for qualitative dimensions of this study.

Additionally, respondents were asked to plot themselves on a 2 x 2 matrix (-5 to +5 scale) of interdisciplinary comfort level (y-axis) and intercultural comfort level (x-axis). The matrix was designed to gauge respondents' degree of both cultural and disciplinary comfort in collaborative research after this international experience. Matrix results were added to the quantitative dataset. Correlation analyses were performed on the variables of interest using Spearman's rho, a non-parametric test commonly used with ordinal data to test for rank correlation. Results are reported following Cohen (1988), where moderate correlations occur between (+/-) 0.30 and 0.50, and high correlations are greater than 0.50 or less than -0.50. Positive correlations indicate factors that improved interdisciplinary and intercultural comfort and negative correlations indicate factors that hindered comfort.

Results

After completing the course, interview participants indicated how comfortable they were working in an interdisciplinary, intercultural setting prior to the course versus after. Respondents plotted themselves on a Cartesian coordinate system in comfort level working in interdisciplinary (x-axis) and intercultural (y-axis) settings (Figure 4-3). Comfort level is plotted using a Likert Scale from negative five, meaning no experience or comfort, to positive five, meaning extremely comfortable. Participants experienced an increased comfort level working across disciplines of 1.9. The students experienced an average comfort increase of 2.1 working across cultures because of their Water Issues course experience in Chile.

The interdisciplinary comfort level before the trip correlated positively (moderate significance) with both age of participant at time of trip and years of experience in interdisciplinary research. Age and years of experience in an interdisciplinary setting were highly correlated, as expected. Interdisciplinary comfort after participation in the course had a moderate correlation in the positive direction with the helpfulness of the interdisciplinary activities (i.e., the Toolbox exercise), respondents' age at the trip, and time spent in lectures. There was a moderate negative correlation between current interdisciplinary comfort levels with time spent in field trips (i.e., the more time in the field, the lower the interdisciplinary comfort). Change in interdisciplinary comfort was positively correlated (moderate significance) with the percent composition of North American student within a working group, group social time, and time spent in lectures. Interdisciplinary comfort was negatively correlated (moderate significance) between personal time spent previously in other countries and time spent with Indigenous people in Chile.

Post-course intercultural comfort (i.e., after the Water Issues course) was positively correlated (strong significance) with personal time spent in other countries previously, but negatively correlated (moderate significance) to time spent in lectures during the Chilean experience. The change in intercultural comfort levels because of the trip demonstrated weak positive correlations with group social time and weak negative correlation with time spent in other countries. While the level of fluency in another language showed a strong, positive correlation with time spent in other countries, the correlation was low with cultural comfort indices. Following participation in the Water Issues course, students increased their comfort working in both interdisciplinary ($p = 0.0006$) and intercultural (p = 0.0007) settings at an α level of 0.05. Table 4-1 summarizes the results of the correlation analysis form the survey results.

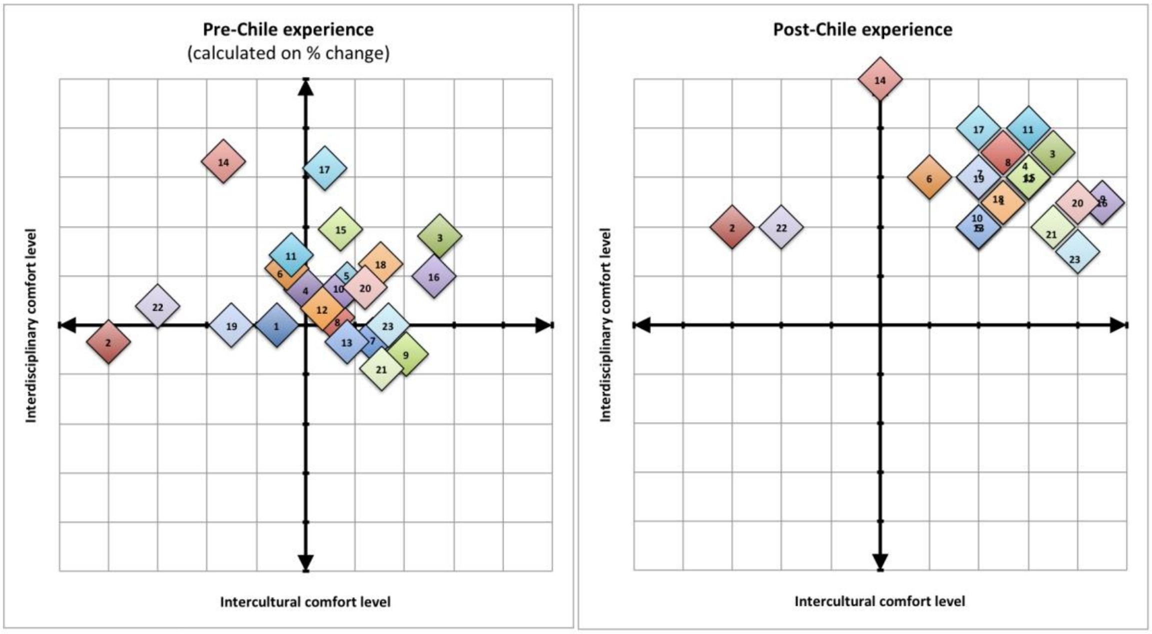

Figure 4-3: Participants self-evaluation of comfort working in an interdisciplinary (on the x axis), intercultural (on the y axis) setting.

Discussion

Of the twenty-three North American students, twenty-one of them had previous experience and course work that explicitly taught how to collaboratively work across disciplinary divides. The average age among the North American cohort when they participated in the Water Issues course was 31, and many had extensive experience working in interdisciplinary settings. Those experiences and backgrounds with formal training were brought into group negotiations in the Water Issues course. Furthermore, the University of Idaho's IGERT program pointedly recruited interdisciplinary students, which was reflected in the relatively high interdisciplinary comfort levels reported by the participants.

Numerous interviewees specifically mentioned barriers to disciplinary adequacy. For example, one respondent felt that "engineers struggled to grasp what the biologists were saying." Through various forms of language and disciplinary translation within the group, others were able to understand the biological concerns better, even though the disciplinary trust was never fully achieved. To facilitate disciplinary adequacy, some groups turned to scholarly literature outside their respective

Table 4-1: Summary of the correlation analysis completed using Spearman-Rho's correlation testing for non-parametric data.

Primary Variable	**Secondary Variable**	**Spearman's Rho**	**Correlation Strength**	**Direction**
Interdisciplinary Comfort Before Participation in the Water Issues Course	Participant Age While in Water Issues Course	0.409	Moderate	Positive
	Number of Years Working in an Interdisciplinary Setting	0.475	Moderate	Positive
Interdisciplinary Comfort After Participation in the Water Issues Course	Usefulness of Interdisciplinary Activities (e.g., Toolbox)	0.363	Moderate	Positive
	Participant Age While in Water Issues Course	0.326	Moderate	Positive
	Time Spent in Field Trips	-0.421	Moderate	Negative
	Time Spent in Lectures	0.366	Moderate	Positive
Change in Interdisciplinary Comfort	Percent Group Composition of North American Students	0.403	Moderate	Positive
	Amount of Social Time with Group	0.369	Moderate	Positive
	Previous Time Spent in Other Countries	-0.315	Moderate	Negative
	Time Spend with Indigenous Groups	-0.480	Moderate	Negative
	Time Spent in Lectures	0.499	Moderate	Positive
Intercultural Comfort Before Participation in the Water Issues Course	Participant Age While in Water Issues Course	0.610	Strong	Positive
	Previous Time Spent in Other Countries	0.504	Strong	Positive
Change in Intercultural Comfort	Time Spent in Social Settings	0.285	Weak	Positive
Intercultural Comfort After Participation in Water Issues Course	Previous Time Spent in Other Countries	0.585	Strong	Positive
	Time Spent in Lectures	-0.316	Moderate	Negative
Participant Age While in Water Issues Course	Number of Years Working in an Interdisciplinary Setting	0.610	Strong	Positive
Fluency Level in Other Languages	Previous Time Spent in Other Countries	0.521	Strong	Positive

fields. Not all groups had the same perspective or difficulties integrating. One respondent stated, "differences (are) in tools, rather than disciplines."

Hammer and Bennett's Intercultural Development Continuum (Figure 4-2) shows the process that individuals undertake to develop intercultural mindsets. Working across disciplinary bounds follows a similar continuum. During the Water Issues course, each student joined the course with their own experience and progress working through interdisciplinary and intercultural continuums. Their experiences were brought into the course and leveraged to aid in the class project. The post-survey results do not account for the students' pre-course experience and comfort levels. However, the experience aided in further developing the skillset and comfort necessary (as shown by the results of the correlation analysis) to further progress individuals across disciplinary and cultural continuums.

Results of the interviews and the correlation analysis show that the best methods to facilitate interdisciplinary efforts were to: 1) have a formal instructional setting, and 2) allow for open discussion of disciplinary differences within teams. A key component in the group discussions—as one interviewee stated—was to allow for "open and honest" conversations and to be "willing to debate both intellectually and jokingly and share and listen." The open dialogue allowed members to "discover how each member viewed things to get beyond that sticking point." Interestingly, all the participants who mentioned the different interdisciplinary processes in the interview reported a high level of interdisciplinary comfort (average of 8.5 out of 10) following the Water Issues course. The high level of interdisciplinary comfort allowed groups to apply interdisciplinary tools to overcome interdisciplinary hurdles.

Many of the students had previously studied or lived in immersive international settings. Eight considered themselves competent or fluent in at least one other language. Six additional students felt they could "get by pretty well" in another language. Twelve had at least some knowledge of Spanish. The previous intercultural comfort that these students brought to the course helped move them across the Intercultural Development Continuum.

In contrast to the interdisciplinary process, however, students were not provided with methods to embrace intercultural differences in the Water Issues course. The curriculum provided on-site cultural experiences in Chile but did not address other influential program components identified in IDI literature to increase intercultural adequacies, such as: pre-departure and re-entry preparation, cultural mentoring, and reflection on intercultural experiences (Jackson 2009; Hammer 2012; Egidiussen Egekvist et al. 2016). Bennett (2010) laments that a major impediment to intercultural learning in studies abroad is the "failure as international educators to be knowledgeable protagonists of intercultural learning" (p. 446). Indeed, we discovered that for most of the Water Issues cohorts, our interviews were the first time they had been asked to reflect on the experience—in some cases this was four years later.

It is therefore no surprise that the need to integrate cultural consideration into interdisciplinary research was not discussed in the context of the course, which was one impetus for this study. Interviewees were asked if any cultural differences or barriers occurred while working on the group project. Eleven respondents out of the twenty-three either implied or explicitly stated that cultural differences arose while working on the international teams; ten mentioned that they did not notice cultural differences. Two of the interviewees stated that either they or members from their group had previously spent time in Chile, which may have increased intercultural adequacy between team members.

Results showed that people who self-reported feeling more comfortable working across cultures were less aware of the existence of cultural differences; this falls in line with the Dunning-Kruger effect of being ignorant of one's own ignorance (Dunning 2011). Participants who observed distinct cultural differences, self-reported an average cultural comfort level of only 6.7. In contrast, the individuals who claimed that they did not notice cultural differences responded with a higher average cultural competence, 7.7. However, one student who self-reported an experience of severe culture shock was well aware of their own limitations and ranked their intercultural comfort the lowest of the cohort. Both survey and interview results suggest that time spent in social settings helped to foster intercultural comfort, whereas formal, lecture-based settings inhibited comfort in working across cultures.

Differences also arose among all the groups around the idea of how rivers should be managed—these are issues that are neither clearly disciplinary nor completely cultural—and were evident in the surveys and interview transcripts. As an example, one interviewee noted that:

> *People in Chile don't have the same perspective on the environment than we [Americans] do; Americans came in with "dams are bad" while Chileans wanted to make their country great through the development of hydropower*.

In the authors' working group, the North American students advocated for limiting or even removing dams from riverine systems to allow for the restoration of natural processes. Being from the Columbia River Basin, the North American students have seen how dams, over time, have become the primary contributor to ecological consequences, such as a large decline in salmon populations. In contrast, Chilean students appreciated the importance of dams in their economy. The Chilean students were in favor of installing additional infrastructure, with limits, to hold water for future use, including electricity generation and irrigation. Further, while Chilean academic communities embrace the importance of biodiversity and species preservation, the endemic species within the Laja and Biobío River systems are not iconic species and do not occupy preeminent cultural status, such as salmonids do in the American Pacific Northwest. Many interviewees discussed differences between the native species located in the Biobío and Laja River systems compared to the Colombia River. One American interviewee stated that the Chilean rivers lacked native "charismatic megafauna" within the river systems like the iconic salmon in the rivers of the Pacific Northwest.

Within the Chilean river system, many of the endemic species are dissimilar to endemic species that the American counterparts find in their river systems. The North Americans were interested in preserving endemic species, but one observed that:

> *Chilean culture doesn't have the connection with the fish, especially because the endemic fish are small galaxids*[2] *and of no particular cultural value*.

Some students struggled with the differing viewpoints regarding endemic species between the salmon and steelhead in the Pacific Northwest to the small fish species in the Chilean rivers. One interviewee stated that, "we Americans had to get over it," meaning the North American students had to grasp and understand differing cultural views on endemic species. To ensure that the proposed outcomes from the class project were favorable within the Chilean setting, the North American students needed to re-evaluate their ideas about dams and fish to include the cross-cultural perspective of both the locals and North American students.

Proposing a Methodological Framework

While working on the group project, our team (the co-authors) was able to work through the beginning steps of the interdisciplinary process of building disciplinary adequacy, facilitating disciplinary trust, and developing a conceptual model of the system. For these steps we drew on our lecture and field trip notes, our individual specialties, generous use of a white board, and the previous experiences of interdisciplinary experience of two group members. However, we had trouble building a conceptual model and could not agree upon an integrating question. Our progress was at an impasse.

Through conversation we realized that the North American students and the Chilean students had different cultural perspectives on dams and river operations (as elaborated above). The

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[2] Adult *Galaxias maculatus* specimen average only 10.5 cm (Froese and Pauli 2017)

underlying differences on dams crosscuts both disciplinary and cultural differences, contexts, and perspectives. Reflecting on the interdisciplinary objectives of our course, we realized there was a gap in the process: there was no discussion of cultural differences. At this point in the interdisciplinary process (building a conceptual model and developing an integrating question), we were able to facilitate a supportive conversation regarding the different cultural views of dams. The resulting integrating question allowed for a solution with reasonable regionally relevant ecological compromises, rather than an absolutist approach.

In the synthesis phase of our project, an unexpected but particularly interesting cultural impasse occurred over the definition of time. The future, in Euro-American culture, is typically represented in a discrete time frame. As an example, management plans will have a time horizon of five, ten, or even 30 years. Our Chilean colleagues had a different understanding of what it meant to even articulate a time horizon. To explain the Chilean concept of the future, our colleagues told the folklore story of Pedro Urdemales (Memoria Chilena n.d.). In the story, Pedro promises his soul to the devil, payable tomorrow. Whenever the devil comes to collect, Pedro tells him that he promised to pay tomorrow; but it is currently today. Thus, the idea of tomorrow—or the future—remains an indefinite concept that can always be pushed onward. In essence, there are different views of timelines between the North and South American cultures. By revisiting the cultural context throughout the interdisciplinary process, we were able to blend both the North and South American students' perspective into our process. We designed our management schemes to reflect the cultural difference by not defining specific periods, but in casting the solutions on relatively "short," "moderate," and "long-term" time horizons.

Figure 4-4 demonstrates the addition of cultural-based discussions to build cultural adequacy during the interdisciplinary process. By adding cultural discussions, we were able to collaborate on an international interdisciplinary research/management project. Our group did not experience place-based cultural differences until we started developing a conceptual model of the water management issue. Other teams encountered process-slowing issues at other times in the cycle. It is prudent to check the intercultural adequacy of the members frequently, and iteratively, throughout the interdisciplinary process. Revisiting the cultural context of the interdisciplinary process at every step ensures that place-based cultural perspectives are being addressed throughout the process so that the integrative results are meaningful in the regional context and local communities.

While the Water Issues course took place with students between North and South America, the overarching theme of intercultural adequacy applies to water management throughout the United States. For example, in the arid west Native American tribes play a critical role in water management in numerous basins, for example the Pyramid Lake Paiute Tribe in the Truckee River Basin, California/Nevada (Cosens 2003); Yakima Nation in the Yakima River Basin (Graham 2012). The cultural value of water and fisheries can differ largely from the cultural value of water for farmers and power producers (e.g., Freeman 2005). Building intercultural adequacy can help bridge between cultural viewpoints and further support the intercultural aspects of integrated water resource management.

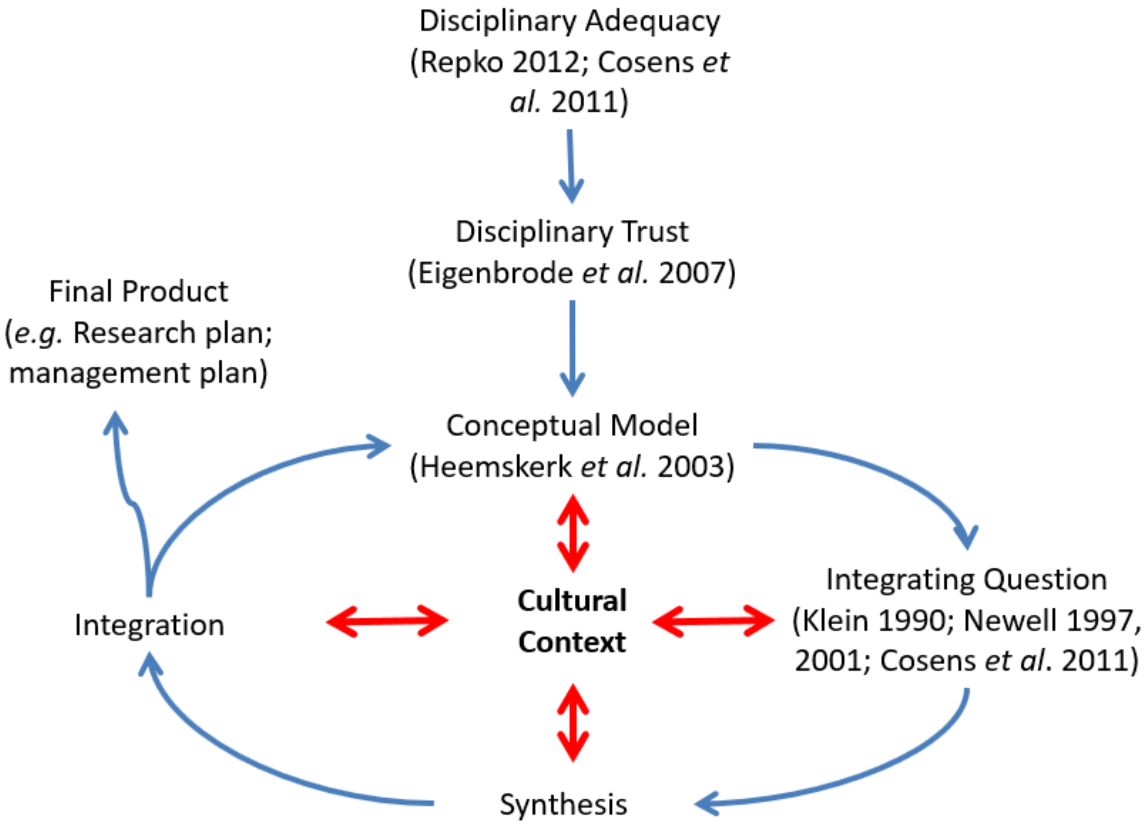

Figure 4-4: The interdisciplinary process presented in Cosens et al 2011 with the addition of cultural discussion feedback loops throughout.

Conclusion

The international collaborations of faculty at the University of Idaho with their counterparts at Universidad de Concepción and Universidad Católica de la Santísima Concepción made a space for a creative interdisciplinary, intercultural experience. Results from the interviews and surveys conducted in this research suggest that increased time in formal settings, such as lectures, aids in increasing interdisciplinary collaboration. In contrast, however, more time in informal situations and team interactions was needed to foster intercultural learning and collaboration. Balance is needed between time spent in formal and social/informal settings to work effectively across intercultural and interdisciplinary bounds.

The Water Issues course improved students' comfort level working across interdisciplinary and intercultural boundaries. A short, culture-focused immersion course could facilitate individuals' comfort in working across boundaries. Groups working across cultural and disciplinary boundaries could benefit by starting their experience in a similar setting. Our findings have broad applicability in interdisciplinary and intercultural settings. Water resource management interlinks numerous disciplinary fields and binds cultures together. Interdisciplinary and intercultural education programs train the next generation of natural resource managers who need to blend complex needs of society and the environment. Collaborators in fields like water resource management must learn how to work across disciplinary and cultural divides including ideologies and cultural philosophies, as demonstrated in our different working approaches to space (e.g., landscapes, dams, and biota) and even to time. People and landscapes should be interpreted with context and history (Swensen et al. 2013) to understand place-based and heritage cultural perspectives. Groups need to develop intercultural adequacy when working on interdisciplinary teams with members from different countries and bioregions and acknowledge that perspectives on natural systems can differ.

Trust and understanding take time to build. More activities than just working together are needed to overcome intercultural adequacy. Good facilitation and support before, during, and after a study visit aid in developing intercultural competencies (Jackson 2009; Egidiussen Egekvist et al. 2016). Getting to know teammates' stories, such as where each person came from, further links conversations back to the connections between people and the local environments (Allen et al. 2014). In the intercultural setting, our research found that there is value in moving away from traditional lecture-style presentations to more personal interactions to foster intercultural adequacy. Social interaction time helps "move the emphasis of the research discussions away from just the technical issues (how to do it) towards the aims (what to do and why)" (Allen et al. 2014, p. 11).

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Chapter 5: Conclusion

Forest managers are faced with balancing complex ecosystems, often with limited resources. Optimizing management requires managers to review scientific literature, develop methods, conduct experiments, and draw conclusions. Because of the complexity of systems, forest managers then must collaborate to implement new solutions to protect our natural resources.

My dissertation research followed a similar forest or natural resource management track. In the beginning, I was asked a question by Dr. Craig Cooper, a water quality manager for the Idaho Department of Environmental Quality. Dr. Cooper asked, "can we predict phosphorus loading for forest systems?" To answer his question, I reviewed the scientific literature and completed preliminary soil sampling. The sampling showed interesting results; soil P pools were different before and after a fire. To quantify soil P shifts, I developed a new method to reproduce wildfire in a laboratory setting for soil environments. Then, I was able to quantify shifts in soil P and soil carbon before and after a fire. Finally, my last chapter proposes an addition to the interdisciplinary collaborative process to include discussion regarding place-based cultural differences. Figure 5-1 summarizes the research path completed while working on my dissertation.

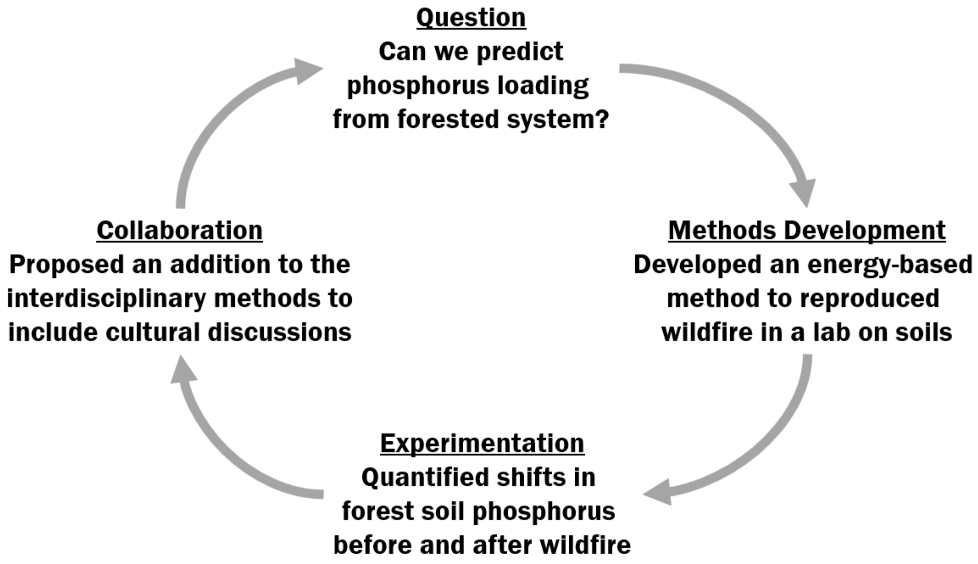

Figure 5-1: Research path followed for my dissertation—matching the typical path that forest and natural resource managers follow when facing challenges.

Reproducing Wildfire and Controlled Burns in a Laboratory Setting

The impacts of wildfire on soils have been researched for more than half a century. In many experiments, researchers have turned to laboratory-based experiments to control variables, such as intensity, burn times, soil moisture (Certini, 2005; Glass et al., 2008; Robichaud and Hungerford, 2000). Numerous methods have been used as surrogates of fire in a laboratory, such as heating soils in muffled furnaces (DeBano et al., 1976; Debano and Krammes, 1966; Doerr and Moody, 2004; Marcos et al., 2007; Sertsu and Sanchez, 1978), using heat guns (Wieting et al., 2017) or heating lamps (Cancelo-Gonzalez et al., 2015, 2012; Debano et al., 1979). Other researchers directly burnt samples by direct flame via propane torches (Gabet, 2014; Stoof et al., 2010). To date, there is not a standard method to test the impact of fire on soils in a lab.

In addition to the various approaches to heat or burn soils in a laboratory, there have been just as many approaches to determine the end of the point of treatment. Robichaud and Hungerford (2000) ended the experiment when the soil temperatures reached 100 to 150 °C, 250 to 300 °C, and 400 to 450 °C. Stoof et al. (2010) ended their experiment when soil surface temperatures reached 900 °C. Cancelo-Gonzalez et al. (2012, 2015) ended their experiment when the soils reached 200 °C to reproduce medium severity burns and 400 °C for high severity burns. Gabet (2014) sampled soils at intervals between 250 to 1,025 °C. Across the research past, there is no standard approach to reproduce wildfire in a laboratory setting onto a soil.

Chapter 2: Reproducing Wildfire in a Laboratory Setting proposes a new standardized method to reproduce wildfire in a laboratory setting that is quantitative, mechanistic, and replicable following a new standard set forth by Smith et al. (2017). The new method applies a mechanistic approach to applying a known amount of radiative energy to a soil. The method allows soils to have direct flame contact, similar to what is experienced in nature.

Forest Soils Response to Fire Radiative Energy Dosing

Many alpine lakes, including high profile lakes such as Lake Tahoe and Coeur d’Alene, are P limited (Goldman, 1988; Schindler, 1977; Woods and Beckwith, 1997). Increased P loading will lead to increased eutrophication, which is the leading cause of water quality impairment in the United States (Sharpley et al., 2003; U.S. Environmental Protection Agency, 1996). Soil P management is critical in forested alpine systems to ensure the protection of downstream water quality.

Wildfire has long been known to alter a soils’ physical structure (Certini, 2005; Debano, 2000; Garcia-Corona et al., 2004). Wildfire is also known to change nitrogen (Glass et al., 2008; Johnson et al., 2014) and carbon cycling (Adams, 2013; Beringer et al., 2003; González-Pérez et al., 2004) with a soil. However, less is known regarding fire’s impact on soil P.

Chapter 3: Forest Soils Response to Fire Radiative Energy Dosing focused on quantifying shifts in soil’s water extractable P (WEP) and total P (TP) content and concentration in wet and dry soils before and after a simulated wildfire in a laboratory setting. Following the simulated fire, WEP content decreased in both the wet and dry soils. Decreases in WEP were more extensive (50% compared to 33%) when the soil was wet compared to the dry soils. TP shifts before and after the fire were minor and insignificant.

Results from this study can help forest managers develop plans to reduce P loading further. This showed larger considerable decrease in WEP, the form of P most available for uptake by plants and algae, when the fire occurred on wet soils compared to dry soils. Forest managers looking to manage biologically available P may want to apply controlled burns when the soils are still moist compared to when it is dry to reduce WEP loads.

Integrating Cultural Perspectives into International Interdisciplinary Work

Forest and natural resource management is a complex field that requires a detailed technical understanding of many systems, such as soils, forests, habitat management, water quality, and recreation management. To successfully manage forests, managers must work collaboratively across disciplinary bounds to integrate various field complexities.

The interdisciplinary research field has developed a standardized process to work collaboratively across disciplinary bounds while working in complex environments. The formalized process begins by building disciplinary adequacy (Cosens et al., 2011; Repko, 2012) and disciplinary trust (Eigenbrode et al., 2007). Once an interdisciplinary team understands and trusts the various disciplines represented, teams should build conceptual models (Cosens et al., 2011; Heemskerk et al., 2003) and use those models to developed integrating questions (Cosens et al., 2011; Klein, 1990; Newell, 2001). The integrating question and conceptual model serve as a discussion piece and lead the research and integration process. The framework on the left of Figure 5-2 shows the interdisciplinary research process.

While working in an interdisciplinary, intercultural team in a water resource focused course with students from North and South America, our team realized that the interdisciplinary framework did not discuss cultural differences. We also found that our placed-based cultural viewpoints differed, and those differences needed to be discussed so that we could understand each other. In essence, we learned that we needed to build cultural adequacy (like disciplinary adequacy) so that we collaborate. Integrating Cultural Perspectives into International Interdisciplinary Work proposes the addition of cultural context to the interdisciplinary, collaborative research and natural resource management process.

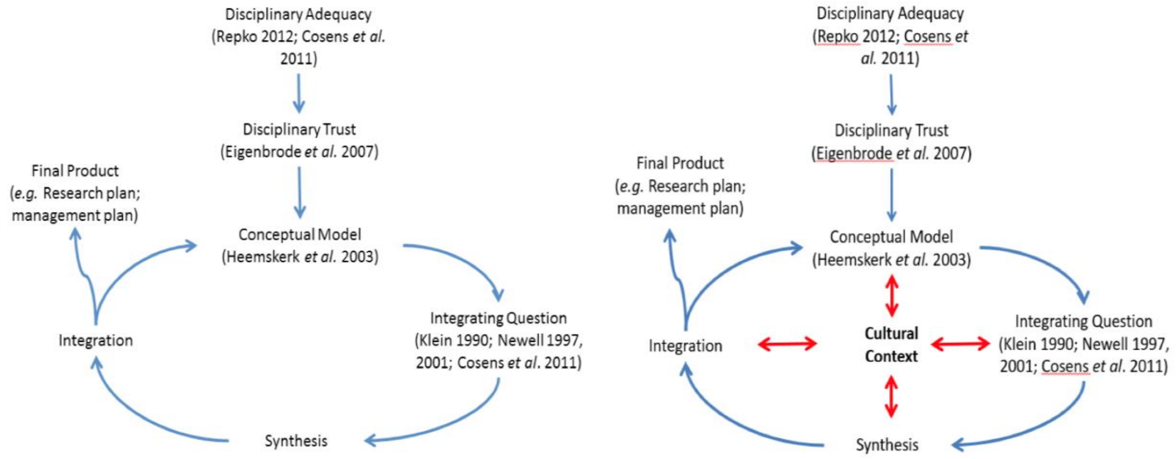

Figure 5-2: The framework on the left summarizes the interdisciplinary research collaboration process, as proposed by Cosens et al. (2011). The framework on the right includes the proposed addition of the cultural discussions to the framework during the collaboration process.

Connecting the Pieces

Forest management is involved. My research focused solely on forest management's soils component—forest managers must consider more than just soils when they make decisions. I hope that this research will help forest managers understand P dynamics following wildfire to protect downstream water quality further. My hope is also that the addition of cultural discussions to the interdisciplinary process will aid forest managers when working across cultural bounds. Many of our beautiful forests share a landscape with peoples of differing cultural backgrounds. Places like Lake Tahoe blends the cultural minds of Washeshu people and the U.S. Forest Service; Couer d'Alene blends the cultures of Schitsu'umsh people and the locals that live around the beautiful lake. We must all work collaboratively to sustain the beauty and the balance of our vast landscapes.

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Appendix A: Catalog of soil sample results from the Coeur d'Alene Basin, Idaho.

During this dissertation research, numerous soil samples were collected from the Coeur d'Alene Basin. The results of the soil sampling efforts are catalogued in this appendix. The sampling effort and methods changed as the results progressed. Therefore, the same information is not available at each sampling location. Latitude and longitude in decimal degrees are provided. Some of the samples were collected using a gridded sampling approach and distance between each sample was so small that the latitude and longitude did not report any change. The results present total carbon (TC) in units of grams of TC per kilogram of soil; total phosphorus (TP), Mehlich-III phosphorus (M3 P), and water extractable phosphorus (WEP) in units of milligrams of phosphorus per kilogram of soil.). TC was determined using a Leco sampler that determines soil carbon via combustion following Methods of Soil Analysis (MSA) Part 3 (1996, pages 963-977). TP was determined following a perchlorate digestion using an ICP following MSA number 9 (1965 pages 1036-37). WEP was determined via a water extraction where soil was placed into deionized water and shaken then filtered. The filtrate was analyzed for P using an ICP.

Latitude	**Longitude**	**TC** **(g_{TC}/kg_{soil})**	**TP** **(mg_{TP}/kg_{soil})**	**M3 P** **(mg_{M3P}/kg_{soil})**	**WEP** **(mg_{WSP}/kg_{soil})**
47.6992	-116.6837		1570	760	25
47.6996	-116.6836		1020	210	25
47.6998	-116.6836		1020	300	30
47.6995	-116.6833		990	210	20
47.6993	-116.6834		980	190	35
47.6994	-116.6836		920	185	15
47.6999	-116.6833		900	215	25
47.6995	-116.6820		860	530	25
47.6998	-116.6830		830	135	25
47.6996	-116.6830		780	125	15
47.6997	-116.6820		730	145	10
47.6992	-116.6820		2770	585	20
47.6989	-116.6837		2340	535	15
47.6990	-116.6831		2010	455	10
47.6990	-116.6837		1710	620	15
47.7002	-116.6833		1680	1020	20
47.7003	-116.6835		1530	800	25
47.7000	-116.6836		1350	785	25
47.6988	-116.6833		1320	630	15

47.6990	-116.6834		1200	540	25
47.6991	-116.6831		990	430	15
47.7005	-116.6835		970	605	25
47.6993	-116.6831		860	490	20
47.7001	-116.6830		830	305	15
47.6999	-116.6820		830	495	30
47.7001	-116.6820		750	255	15
47.6993	-116.6820		580	270	10
47.6988	-116.6819		3960	1375	35
47.6986	-116.6820		3310	1390	25
47.6983	-116.6820		3070	915	25
47.6984	-116.6819		2870	785	20
47.6981	-116.6821		2790	1125	35
47.6988	-116.6831		2260	1005	40
47.6985	-116.6830		2220	1010	25
47.6990	-116.6820		2200	215	10
47.6986	-116.6833		1710	775	20
47.6983	-116.6830		1360	635	15
47.6986	-116.6837		1260	825	25
47.7008	-116.6820		1230	470	25
47.7007	-116.6835		970	490	20
47.7010	-116.6818		960	220	10
47.7004	-116.6833		940	385	25
47.7003	-116.6830		930	430	20
47.7006	-116.6820		890	345	25
47.7003	-116.6820		780	220	20
47.6982	-116.6833		1930	970	25
47.6978	-116.6820		1700	750	25
47.6984	-116.6833		1250	640	20
47.7006	-116.6830		1070	400	15
47.6981	-116.6830		870	450	10
47.7015	-116.6819		840	450	15
47.7013	-116.6818		520	75	10
47.7435	-116.6122	78.63	930	105	4.5
47.7436	-116.6127	105.21	1450	240	9.5
47.7436	-116.6128	35.88	850	100	1.5
47.7437	-116.6133	16.37	310	145	9
47.7437	-116.6135	29.91	320	200	19
47.7462	-116.6117	113.51	1110	280	14
47.7458	-116.6117	164.13	1250	340	31.5
47.7456	-116.6119	79.25	2250	465	9.5
47.7457	-116.6123	130.07	1090	295	18
47.7282	-116.6479	55.26	750	150	1.5

47.7282	-116.6493	64.42	1640	535	5
47.7283	-116.6503	34.99	530	35	3.5
47.7284	-116.6502	52.12	590	140	4.5
47.7284	-116.6502	40.27	1910	735	7
47.7277	-116.6468	28.88	940	170	4
47.7280	-116.6478	128.91	1150	310	14
47.7275	-116.6460	14.3	490	235	20.5
47.7273	-116.6461	110.25	1350	730	35.5
47.7276	-116.6465	27.19	600	115	5.5
47.7166	-116.7265	54.11	1880	655	11.5
47.7164	-116.7263	60.5	1630	750	14.5
47.7163	-116.7261	53.88	1700	870	16
47.7162	-116.7259	36.26	1680	660	10
47.7159	-116.7258	41.4	750	340	10
47.7198	-116.7248	40.69	590	165	12.5
47.7197	-116.7245	35.96	950	355	15.5
47.7196	-116.7244	27.85	620	105	6.5
47.7194	-116.7242	75.15	1080	960	57.5
47.7192	-116.7240	55.27	740	260	23
47.7189	-116.7239	84.41	790	370	28.5
47.6624	-116.7734	66.28	742	300	1.5
47.6627	-116.7739	63.38	824	505	31
47.6627	-116.7739	60.62	470	220	23
47.6630	-116.7741	92.41	1051	665	12
47.6634	-116.7752	41.24	679	320	22.5
47.6669	-116.7784	55.67	1104	525	8
47.6713	-116.7788	67.78	1200	450	14
47.6678	-116.7791	58.08	941	275	10.5
47.6683	-116.7790	72.19	1246	280	7
47.6689	-116.7791	97.39	1420	1235	22
47.5167	-117.0397	23.94	610	285	15
47.5192	-117.0381	17.44	740	170	5
47.5183	-117.0294	18.07	400	155	10
47.5183	-117.0172	17.57	480	115	10
47.5133	-117.0058	21.32	610	340	10
47.5133	-117.0064	27.47	600	205	20
47.5144	-117.0072	27.56	560	360	15
47.5106	-117.0072	28.6	760	570	30
47.5100	-117.0069		630	320	15
47.4950	-117.0308	17.22	560	245	20
47.4942	-117.0308	20.96	660	250	20
47.4939	-117.0311	13.56	510	225	20
47.4922	-117.0281	18.01	510	180	10

47.4919	-117.0278	12.73	500	245	25
47.4842	-116.9881	25.14	840	135	25
47.4861	-116.9925	36.68	580	160	10
47.7405	-116.1608	69	1184	280	10
47.7408	-116.1609	76	1069	410	5
47.7409	-116.1610	62	726	160	10
47.7410	-116.1606	76	780	335	10
47.7412	-116.1603	60	859	295	5
47.7411	-116.1600	65	1246	425	5
47.7408	-116.1604	59	710	330	5
47.7408	-116.1602	69	1081	160	5
47.7409	-116.1600	72	1290	425	5
47.7511	-116.1450	110	1542	655	25
47.7510	-116.1453	78	1439	240	10
47.7511	-116.1453	88	1110	115	10
47.7513	-116.1451	133	1140	340	15
47.7515	-116.1500	93	1360	185	10
47.7513	-116.1447	85	1310	115	10
47.7512	-116.1448	95	1620	355	15
47.7512	-116.1443	74	1490	280	15
47.7515	-116.1441	91	1545	375	15
47.7515	-116.1441	91	1545	375	15
47.7515	-116.1441	91	1545	375	15
47.7360	-116.1916	76	1455	265	10
47.7359	-116.1920	81	2677	430	10
47.7357	-116.1923	163	1266	365	30
47.7357	-116.1926	139	1126	290	20
47.7358	-116.1926	33	478	135	10
47.7360	-116.1925	25	514	115	10
47.7362	-116.1924	34	543	125	10
47.7362	-116.1922	110	1090	160	20
47.7359	-116.1923	110	1077	110	10
48.8003	-117.2333	49	1320	470	10
48.8003	-117.2329	59	740	305	10
48.8003	-117.2325	40	530	155	0
48.8000	-117.2333	42	1230	420	5
48.8000	-117.2329	54	690	175	5
48.8000	-117.2325	36	640	345	5
48.8000	-117.2325	36	640	345	5
48.8000	-117.2325	36	640	345	5
48.7997	-117.2333	59	470	95	5
48.7997	-117.2329	43	800	100	0
48.7997	-117.2325	36	900	245	5

48.8011	-117.2310	34	1420	380	5
48.8013	-117.2313	26	700	95	0
48.8015	-117.2316	48	1340	365	5
48.8013	-117.2308	32	1450	495	5
48.8013	-117.2308	32	1450	495	5
48.8013	-117.2308	32	1450	495	5
48.8013	-117.2308	32	1450	495	5
48.8014	-117.2311	39	530	105	0
48.8016	-117.2313	76	2510	505	5
48.8014	-117.2306	29	830	330	5
48.8015	-117.2308	27	1040	315	5
48.8017	-117.2310	44	1510	240	5
48.8034	-117.2312	60	1320	515	15
48.8036	-117.2315	76	1020	165	10
48.8036	-117.2315	76	1020	165	10
48.8036	-117.2315	76	1020	165	10
48.8036	-117.2315	76	1020	165	10
48.8037	-117.2317	58	1340	400	10
48.8036	-117.2309	29	710	265	10
48.8038	-117.2311	33	550	110	10
48.8039	-117.2313	46	1450	355	10
48.8038	-117.2307	54	470	110	5
48.8039	-117.2309	32	490	100	5
48.8040	-117.2311	38	510	145	5
47.6814	-116.6056	54.71	890	205	20
47.6908	-116.6061	52.99	780	175	25
47.6911	-116.6056	35.51	580	130	10
47.6922	-116.6050	45.58	1580	600	10
47.6919	-116.6050	38.03	570	205	20
47.6936	-116.6047	52.67	640	140	20
47.6994	-116.6025	42.47	210	35	15
47.6997	-116.6019	33.89	400	105	20
47.6989	-116.6039	74.28	580	205	20
47.6395	-116.6177	45.1	410	125	10
47.6760	-116.5861	50.84	540	145	20
47.6842	-116.5519	114.5	700	245	10
47.6849	-116.5537	32.2	230	70	10
47.6904	-116.5384	46.95	1540	205	10
47.6329	-116.5648	50.16	700	270	15
47.6330	-116.5651	38.59	670	345	20
47.6266	-116.5260	61.95	1290	485	30
47.6303	-116.5403	82.3	780	295	25
47.6320	-116.5359	149.39	630	220	20

47.7316	-116.6179	46.97	920	8	
47.7204	-116.6679	33.96	1070	129	
47.7354	-116.6624	211.33	530	38	
47.7338	-116.6175	48.22	1030	7	
47.7207	-116.6679	72.54	620	36	
47.7348	-116.6628	37.03	2020	144	
47.7414	-116.6189	55.84	4780	33	
47.7190	-116.6716	58.93	4980	35	
47.7338	-116.6617	23.04	780	60	
47.7319	-116.6612	47.77	300	11	
47.7164	-116.6706	82.99	640	12	
47.6819	-116.6872	32.08	650	61	
47.7343	-116.6603	32.37	390	22	
47.7145	-116.6741	57.02	700	39	
47.6841	-116.6881	28.26	900	73	
47.7339	-116.6604	45.13	1230	16	
47.7133	-116.6756	49.81	1000	86	
47.6848	-116.6910	34.15	1160	136	
47.6988	-116.6845	12.49	230	14	
47.7221	-116.6689	62.53	750	6	
47.7132	-116.6766	33.94	400	27	
47.6813	-116.6989	126.69	700	5	
47.6807	-116.7017	73.99	690	3	
47.6806	-116.7030	60.08	860	5	
47.6985	-116.6848	39.12	770	67	
47.7101	-116.6793	63.29	1140	131	
47.6858	-116.6923	57.69	680	18	
47.6707	-116.7474	61.82	1570	174	
47.6857	-116.6941	152.42	980	29	
47.6761	-116.7388	4.29	450	8	
47.6773	-116.7127	4.12	460	8	
47.7296	-116.6577	9.41	60	37	
47.6671	-116.6604	7.92	130	26	
47.7339	-116.6612	1.32	50	6	
47.7137	-116.6375	81.56	980	13	
47.7177	-116.6376	53.87	1770	15	
47.7265	-116.6626	87.35	640	14	
47.7281	-116.6486	434.8	126		10
47.6306	-116.5333	516.5	126.5		15
47.6314	-116.5347	437.35	170		10
47.7269	-116.6461	309.05	46.5		10
47.7275	-116.6458	244.75	52.5		7.5
47.7275	-116.6461	391.2	81.5		10

47.7168	-116.6675	239.7	550	10
47.7168	-116.6675	204.3	520	15
47.7168	-116.6675	274	540	10
47.7168	-116.6675	182.8	450	10
47.7168	-116.6675	255.8	500	10
47.7168	-116.6675	460.7	700	10
47.7168	-116.6675	346.7	610	10
47.7168	-116.6675	393.2	650	15
47.7168	-116.6675	342	510	10
47.7168	-116.6675	334.4	560	10
47.7168	-116.6675	510	636	20
47.7168	-116.6675	391.4	800	25
47.7168	-116.6675	509.5	680	15
47.7168	-116.6675	503.3	570	10
47.7168	-116.6675	352.4	620	10
47.7168	-116.6675	193.4	530	10
47.7168	-116.6675	255.4	560	10
47.7168	-116.6675	207.7	570	10
47.7168	-116.6675	244.7	490	10
47.7168	-116.6675	227.8	510	10