Impacts of Forest Fires on Drinking Water Quality in North America

2010

FRST 497

Amity Chiang

4/12/2010

Abstract

The amount of area burned by wildfire has greatly increased due to human and industrial practices. Therefore, it is crucial to identify the hazards and take actions to prevent the frequent occurrence of wildfires. This research essay is focused on the effect of forest fires in North America on drinking water quality. Review of journal articles, government websites, and other electronic sources indicates that concentrations of nitrogen (especially on nitrate and ammonium), which can be toxic and harmful to human health, typically increase following wildfire. Post fire concentrations of nitrogen in streams depend on the amount of soil erosion and runoff. Other parameters that are affected include chemicals in fire retardant, water temperature, and water pH levels. This essay also examines several postfire options to serve as long term preventative measures.

Key Words: *nutrients, nitrogen, sediments, turbidity, fire retardant, rehabilitation.*

Table of Contents

List of Figures

List of Tables

1.0 Introduction

British Columbia has a great amount of forest and the public is increasingly aware of hazards associated with forest fires, including their effects on watersheds and water quality. The number of forest fires has generally increased from 1998 to 2008 (British Columbia Ministry of Forest and Range). Not only has the number of fires increased but also the total cost of post-fire rehabilitation has increased. For example, in 1998, the total hectares burnt was 76,574 and total cost was $153.9 million, or $2,009.82/ha on average (British Columbia Ministry of Forest and Range). In 2008, 13,233 ha burned with a total cost of $82.1 million, or $6,204.19/ha on average (British Columbia Ministry of Forest and Range). Since forest fires have been increasing for the past 10 years it is crucial to examine the effects on forest fires on drinking water quality.

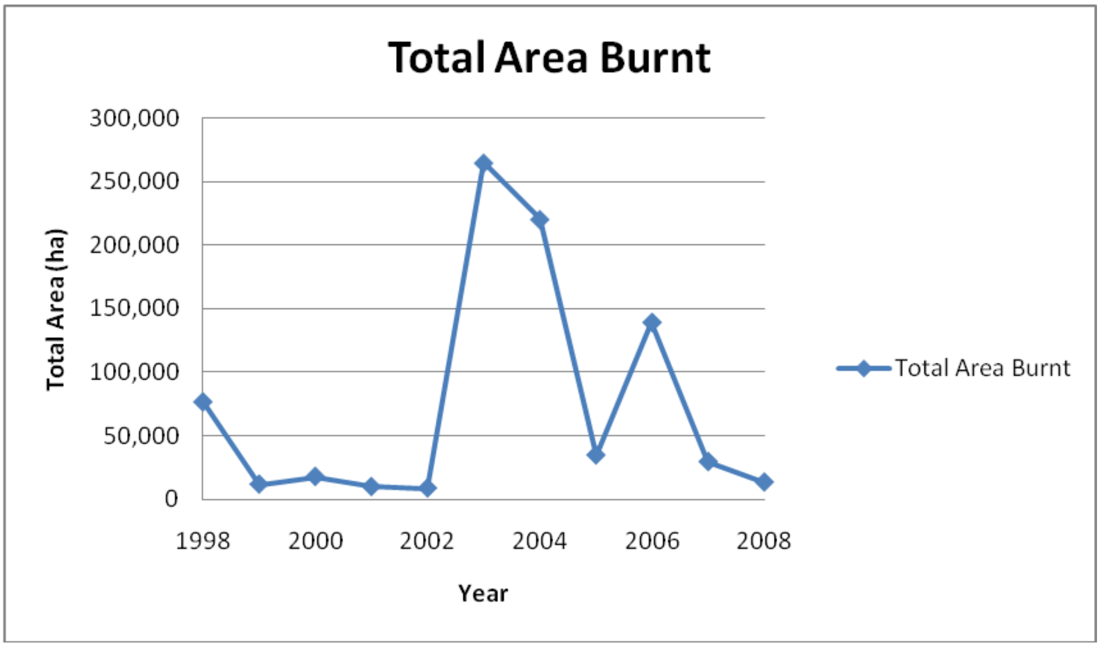

Figure 1: Illustrating the total area burnt from 1998 to 2008 in British Columbia.

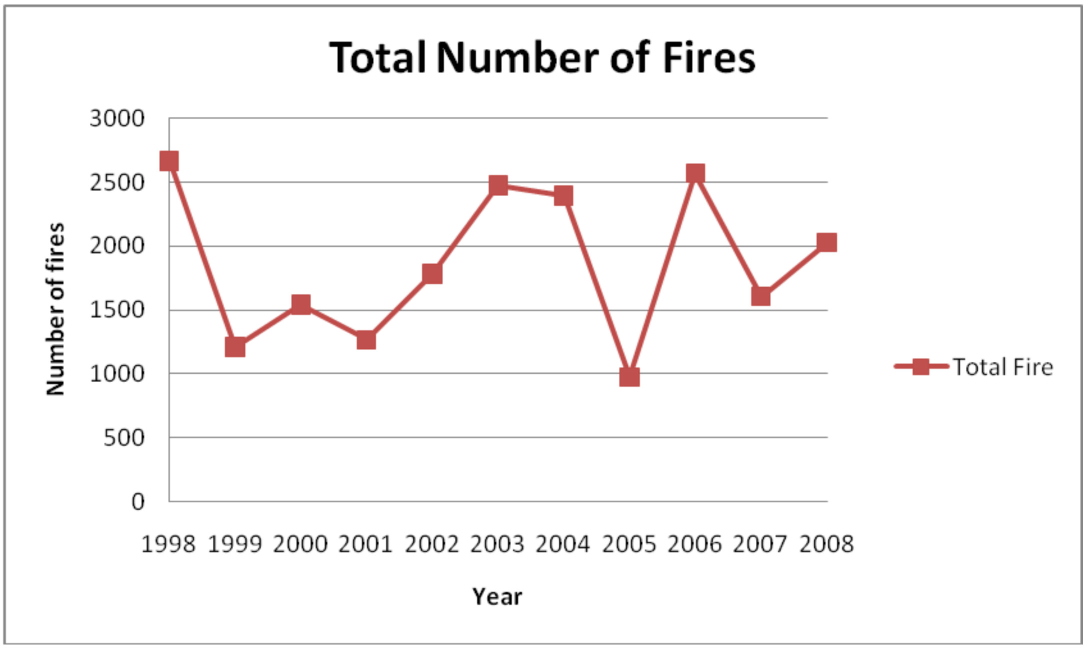

Figure 2: Total number of fires in 1998 to 2008 in British Columbia.

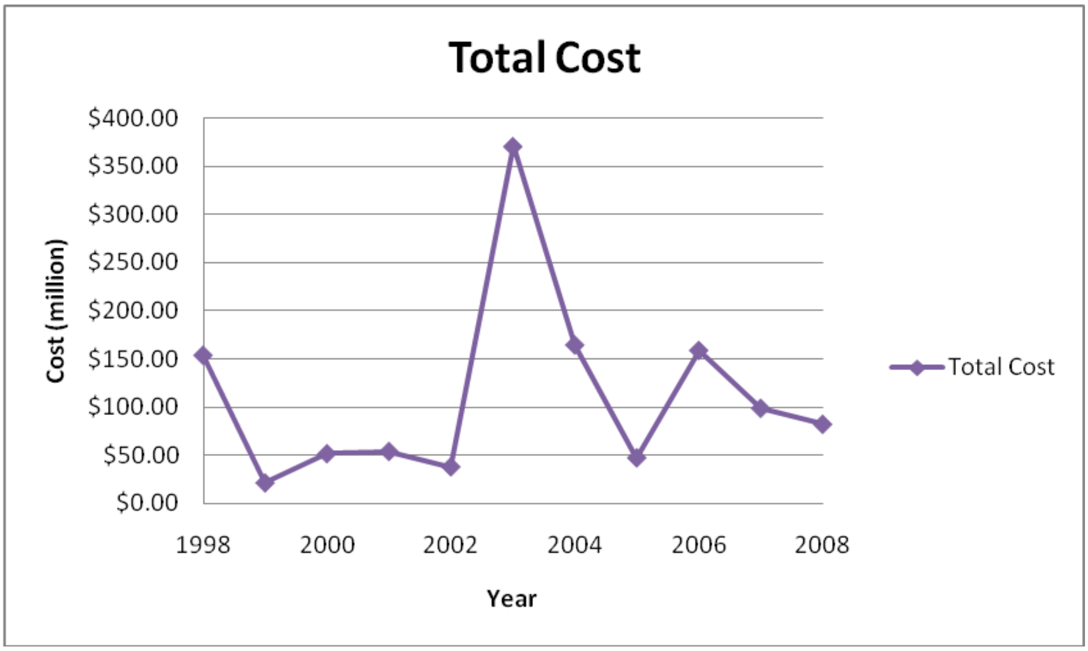

Figure 3: Total Cost (in million) of fire in 1998 to 2008 in British Columbia.

The degree of change to water quality is greatly dependent on fire severity, climate, topography, soil and coverage of burn (Near et al., 2003). Fire severity is classified into three ratings: low, moderate, and high. Low severity fires has low soil heating within 1cm of soil depth and temperature reaches less than 50°C and light ground charring (Neary et al., 2003). The litter layer is slightly scorched and charred while duff layer is still intact (Neary et al., 2003). Moderate severity fires result in light coloured ash present and most wood debris is consumed (Neary et al., 2003). The litter layer is consumed and the duff layer is deeply charred or consumed; within 1 cm depth temperature ranges from 100°C to 200°C (Neary et al., 2003). In high severity fires, soil heating is deep, the duff layer is completely consumed and the top of the mineral layer becomes visibly reddish or orange in color (Neary et al., 2003). Below 1 cm the soil is dark or charred and this may extend down to 10 cm deep (Neary et al., 2003). The impact of wildfires is highly variable due to factors such as climate, soil, topography, and fire severity.

The objective of this essay is to identify the potential impacts of wildfire on water quality, particularly in relation to water quality guidelines for human consumption. The impacts addressed include changes in nutrients, increases in soil erosion and turbidity, and the chemical interaction between fire retardant and water. The essay will also address at what can be done after fire has occurred and possible actions that can be used to prevent wildfires.

2.0 Water quality for human consumption

Drinking water quality is described in terms of the biological, chemical, and physical characteristics of water with respect to human consumption (Pike et al., 2009). Potential water quality effects include on changes in nutrients, especially with nitrogen and phosphorous, which are related to pH level, temperature, and total suspended sediment and turbidity. Also, the chemicals in fire retardant will be examined as a risk to water quality.

Table 1: Summary of British Columbia Approved Water Quality Guidelines (2006).

Substance	Water Use	Guidelines
Chloride (dissolved)	Drinking	less than or equal to 250 mg/L (aesthetic objective)
Chlorite	Drinking	1 mg/L (proposed maximum)
Colour (true)	Drinking	less than or equal to 15 TCU (aesthetic objective)
Colour (true)	Recreation	should not impede visibility in swimming areas
Nitrate	Drinking	45 mg/L as NO_3 (maximum) 10 mg/L as N
Nitrite	Drinking	3.2 mg/L as NO_3 1.0 mg/L as N
Odour	Drinking	inoffensive (aesthetic objective)
pH	Drinking	6.5 to 8.5 (aesthetic objective
pH	Recreation	6.5 to 8.5 (aesthetic objective
pH	Recreation	5.0 to 9.0 (buffering capacity)
Taste	Drinking	inoffensive (aesthetic objective)
Temperature	Drinking	15 degrees Celsius maximum (aesthetic objective)
Temperature	Recreation	30 degrees Celsius maximum
Total dissolved solids	Drinking	less than or equal to 500 mg/L (aesthetic objective)
Turbidity	Drinking	<0.1 NTU (target at all times) 0.3 NTU 95th percentile, 1.0 NTU maximum for chemically assisted filtration 1.0 NTU 95th percentile, 3.0 NTU maximum for slow sand or diatomaceous earth filtration

		0.1 NTU 99th percentile, 0.3 NTU maximum for membrane filtration

2.1 Changes in nutrients

When a fire occurs that consumes all the organic matter, it leaves behind a form of white ash or wood ash (Ranalli, 2004). Wood ash is the inorganic component of the wood that remains after burning (Ranalli, 2004). This inorganic component contains carbonates and oxides of alkali and alkaline earth metals, silica and small amounts of nitrogen, phosphorus and sulphur (Ranalli, 2004). Pike et al. (2009) stated the change in input of two nutrients by wildfires are nitrogen and phosphorous.

2.1.1 Nitrogen

There are different forms of nitrogen (N) including nitrate (NO_3^-), ammonium (NH_4^+), dissolved organic N (DON), total dissolved N (TDN), total particulate N (TPN), and total N (TN) (Bladon et al., 2008). In general these forms of nitrogen are 2 to 4.9 times greater in streams that are burned within two years (Bladon et al., 2008). Blandon et al. (1999) studied that a 350 000 ha plantation of pine in southeastern US showed that nitrate was 7.5 times greater (during the first 2 years of burn the average concentration was 517.9 µg/L), DON was 2.7 times greater (during the first 2 years of burn the average concentration was 365.9 µg/L), TDN was 4.3 times greater (during the first 2 years of burn the average concentration was 892.5 µg/L), and TN was 4.1 times greater (during the first 2 years of burn the average concentration was 635.5 µg/L) in a burned watershed. Lastly, ammonium was 40 times greater in burnt watersheds but this level declined rapidly after a few months after fire occurrence (Binkley et al., 1999). Moreover, the concentration of DON was very high during the first postfire spring because of leaching of highly mobile and resistant mineral N form (Binkley et al., 1999).

Stark (1977) showed that the concentration of nitrate was 2 to 3 times greater during the year after a hot fire occurred in a coniferous forest in Montana. The mobility of nitrate was enhanced when the fire intensity increased with high amounts of biomass and low densities of microbial populations (Chanasyk et al., 2003). Overall, the high concentration of nitrate, TDN and TN was due to the hydrophobic soils, reduced infiltration rates, and increased in runoff capacity (Binkley et al., 1999).

The primary forms of nitrogen of interests for water quality are nitrate and ammonium (Pike et al., 2009) because they influence terrestrial and aquatic productivity (Pike et al., 2009). Another reason that nitrate concentration is significant is because when nitrate concentration is greater than 10 mg/L it can cause methemoglobinemia or "blue baby" syndrome (Binkley et al., 1999). From the BC Ministry of Environment, the concentration of nitrate in drinking water should not exceed 10 mg/L because of this same reason (British Columbia Ministry of Environement, 2010). At 0.03 mgN/L concentration of ammonia (NH_3) it is toxic to aquatic organisms in the short term and concentrations reaching or exceeding 0.002 mgN/L may be toxic in the long term (Binkley et al., 1999). The biological degradation of nitrogenous matter is pH dependent. For example, the concentration of NH_3 increase tenfold when pH decrease by one unit (Pike et al., 2009). The different forms of nitrogen depend on different factors in the nitrogen cycle that can alter human health.

2.1.2 Phosphorous

Phosphorous is a non-toxic nutrient but can influence biological production (Binkley et al., 1999). Phosphorous is obtained from the weathering of minerals through events such as soil erosion and runoff. Hydrophobic soils resulting from hot fires can generate overland flow during snowmelt or rainstorms, promoting increased soil erosion. Thus, increased phosphorous input to streams and lakes is not a direct effect of wildfires but rather an indirect effect related to changes in watershed conditions.

One of Ranalli's (2004) case studies shows that the phosphorous in stream water from a burned watershed was 40 times greater than for the unburned watershed. The exact concentration was 3 µg-P/L on unburned watershed compared to 135 µg-P/L on the burned site within 24 hours after fire occurrence (Ranalli, 2004). This degradation of water quality can leads to increasing concentrations of limiting nutrients that alter the productivity of aquatic ecosystems (Binkley et al., 1999). For example, at high concentrations phosphorous cause unwanted algal blooms and decrease oxygen content for fish to survive, thus leading to drinking water impairment (Wetzel, 2001). Drinking water impairment includes: negative effects on taste and odor, and treatment difficulties (Wetzel, 2001).

Phosphorus has no important gaseous phases (Chanasyk et al., 2003) and is highly variable in concentration throughout the landscape; thus there are no specific water quality guidelines stated (Pike et al., 2009). Nevertheless, phosphorus is a great contributor to color and odor of water as well as indicating the presence of other organic pollutions (Dissmeyer, 2000).

2.2 Total suspended solids, sediments, and turbidity

Total suspended solids (TSS) include clay, silt and very fine sand particles less than 0.1mm in diameter (Pike et al., 2009). TSS is a major concern for drinking water quality because it is able to transport harmful substance and changes in water color that are undesirable for aesthetic reasons (Dissmeyer, 2000). In the study by Silins et al. (2009), the concentration of total suspended solids was 8 times greater in burned watersheds compared to unburned watersheds.

Sediments from wildfire disturbances are often originate from forms of mass wasting and are delivered directly to streams in large quantities (Neary et al., 2003). In particular, rotational stumps near water channels can increase the sediment inputs to streams (Neary et al., 2003). Following mass wasting, the sediment is redistributed onto hill slopes by wind, overland flow, soil creep and/or stream bank failures (Silins et al., 2009). The 8 fold increase in TSS decreased within the first two years after the fire and four years after fire occurrence the concentration was generally small (Silins et al., 2009). Topography and hydro-climatic controls are factors that may contribute to the concentration of sediment in streams (Silins et al., 2009).

2.3 Chemicals in fire retardant

Most fire retardant is comprised of ammonium sulphate or ammonium phosphate (Crouch et al., 2005). The ammonium salts of the retardant will react with cellulosic fuels over the temperature range of pyrolysis combustion (Crouch et al., 2005). In addition, the mineral acid (either phosphoric or sulphuric acid) combines with cellulose to form a higher molecular weight and decrease nitrogen mineralization, which decreases the quantity of flammable hydrocarbons (Backer et al., 2004 and Crouch et al., 2005). Also, some fire retardant may contain sodium ferrocynaide (Backer et al., 2004). The anticorrosive agent will release cyanide (CN^-) when exposed to a certain level of ultraviolet (UV) radiation, which will increase the toxicity of the fire retardant chemicals (Backer et al., 2004). Backer et al. (2004) found 100% mortality of fathead minnows resulting from the use of sodium ferrocynaide. Therefore, ammonia, phosphate, and cyanide can become toxic at high concentrations and is strongly dependent on the pH of the water. For example, at pH 9 the concentration of ammonia is approximately 1 to 2 mg/L. The chemicals in fire retardant will decrease the nitrogen mineralization of fires and may leach into headwater streams.

There are two ways fire retardants can reach a stream: (1) if it is applied away from the surface water, retardant components may enter the surface water during rain or melting events, (2) it can be directly applied over surface waters (Crouch et al., 2005). If fire retardant were applied closely to a water body, it would increase NH_4^+, PO_4^{3-} and NO_3^- concentrations (Dissmeyer, 2000). The short term increase of PO_4^{3-} might result in eutrophication of surface waters (Crouch et al., 2005). However, these increases usually last less than an hour but may reoccur depending on rain events (Pike et al., 2009). When using fire retardant near streams the chemicals will result in short term increase in ammonium and phosphorus.

2.4 Other factors – temperature and pH

Other factors that can alter the rate of chemical reactions include pH and water temperature. pH is a measurement of hydrogen ionic activity and acidity (Buck et al., 2001). The range of pH across the British Columbia is highly variable and depends on the amount of precipitation and rate of alkalinity production in soils and bedrock (McKean & Huggins, 1991). The pH level for drinking water supply in British Columbia is 6.5 – 8.5 and the pH for recreational water is 5.0 – 9.0 (British Columbia Ministry of Environement, 2010). The pH range that is set for drinking water supply is "designed to minimize solubilisation for heavy metals and salt from water distribution pipes" as well as reducing the precipitation of carbonate salts in the distribution system and to maximize the effectives of chlorination (British Columbia Ministry of Environement, 2010). The pH range set for recreational water use is to eliminate the possibility of causing irritation to eyes (British Columbia Ministry of Environement, 2010).

Water temperature is the average kinetic energy of atoms in a solution and measurement of intensity of heat stored (Pike et al.,2009). The measure of temperature in stream water is important because it will affect the rate of chemical and metabolic reactions, viscosity and solubility, gas-diffusion rates, and the settling velocity of particles (Dissmeyer, 2000). Moreover, temperature affects the aquatic organisms' heat-sensitive proteins and enzymes, as well as metabolism, reproduction, and other physiological processes (Dissmeyer, 2000). For example, high water temperature might lead to rapid decomposition of organic material, thus decreasing in oxygen levels (Pike et al., 2009). The drinking water guideline for temperature is 15°C for aesthetic reasons (British Columbia Ministry of Environement, 2010). With decreasing oxygen and reducing oxygen solubility, temperature increases may affect aquatic species (Pike et al., 2009). For example, at temperature range 17 to 20°C, it is thermal stress on juvenile sockeye salmon (McCullough, 1999). Within this temperature range, juvenile sockeye salmon population may be lethal, limiting in metabolism or respiration, and decrease in inhibiting (McCullough, 1999). When water temperature reaches over 15°C it will not only affect aquatic spies but also become unsuitable for human drinking water consumption.

3.0 Rehabilitation and Preventative Measures

The degree of damage caused by wildfires can be highly variable. When forest fires occur, firelines are often built to slow down and eventually put out the fire. These firelines involve soil disturbance, removal of vegetation and the litter layer (Beschta et al., 2004). Post-fire treatments and rehabilitation of the landscape include burn area emergency rehabilitation treatment, restoration consideration, and rehabilitating sites damaged by fire suppression.

3.1 Burn area emergency rehabilitation

Burn area emergency rehabilitation (BAER) treatment is usually carried out to reduce the risk of high runoff and sediment flows to any downstream drinking water intakes and reservoirs (Dissmeyer, 2000). The BAER has different practices such as contour-felled log barriers to decrease the amount of fire spread and broadcast seeding with grasses to reduce erosion during the critical first 2 years after fire occurrence (Dissmeyer, 2000). However, the effectiveness of BAER is highly controversial because contour-felled log barriers have not yet been systematically studied and broadcast grass seedlings did not reduce erosion significantly in general (Dissmeyer, 2000). The application of burn area emergency rehabilitation treatment is currently highly debated because it is not extensively studied.

3.2 Restoration consideration

Restoration consideration is commonly applied to remove standing and downed large wood to eliminate the factors limiting the recovery of terrestrial and aquatic systems (Beschta et al., 2004).

An example of restoration consideration is active restoration, which balances the natural recovery processes and is targeted to reduce sediment production via runoff from firelines and roads (Beschta et al., 2004). For example, when considering soil protection, it is suggested to eliminate the use of ground base salvage logging. If ground based logging is adopted, it will increase the probability of runoff since the soils exhibit hydrophobic conditions and reduce the infiltration of water after fire occurrence (Beschta et al., 2004).

On the other hand, Mclver and Starr (2000) argued that mechanical disturbances to soil could be beneficial because this will discrupt and mix the hydrophobic soils, thus increasesing infiltration rate and reducing overland flow, reduce peak flow, and reduce sediment transport to streams. This argument has been disagreed with Beschta et al. (2004). The counter-arugment was that if the ground based logging is severe enough to mix the soil layers, it would be a greater contributor to accelerated surface erosion and reduced long term soil productivity (Beschta et al., 2004). Moreover, hydrophobic conditions usually last only a few years and post salvage logging on average occurs one year after fire occurrence, which means that by the time logging occurs the soil is no longer water repellent (Beschta et al., 2004). Mechanical disturbance will likely createoverland and increase soil erosion.

3.3 Practices of rehabilitating sites and preventiting wildfire occurance

The intensity and severity of fire is highly dependent on variables such as soil characteristics, topography, and climate. These variables cannot be controlled by human activities; the variables that we could control would be amount of fuel available, type of fuel available, and type of logging activities. Focusing on the different options for rehabilitating burned areas while making minor changes to prevent wildfire occurrence allows forest resource managers to reduce the impact of the next wildfire.

3.3.1 Ban exotic vegetation species

Exotic plant species can increase the flammability of burned sites and provide more forage for grazing animals (Beschta et al., 2004 and Zedler et al., 1983). Exotic species will increase the likelihood of fire reoccurrence because there is high surface to volume ratio, resulting in an available continuous fuel bed that is a great contributor to rapid fire spread, especially with fine fuels such as dried grasses and grass litter are more vulnerable to ignition (Barro, 1987). On the other hand, Backer et al. (2004) argued that broadcast seeding of grasses can reduce hillslope erosion and promote infiltration by using fast growing and non-native annual grasses. In particular, Backer et al. (2004) suggested ryegrass because they are available at low cost and have soil stabilizing fibrous root systems (Backer et al., 2004). In general, banning exotic species establishments will decrease fuel loading.

3.3.2 Control livestock grazing

Grazing livestock on land that has been burned will delay the recovery process. Grazing livestock will cause soil damage, contribute to invasion of exotic species, and thwart vegetative recovery (Belsky et al., 1999). Moreover, this will cause erosion and degrade streams and riparian conditions (Belsky et al., 1999). Restricting livestock grazing on burned sites reduces soil erosion and sediment transport.

3.3.3 Avoid using structures and prohibit new road construction

Examples of structures include sediment traps, wood additions, bank stabilizers, check dams and gabions (Beschta et al., 2004). By prohibiting new road construction near streams, it will decrease surface erosions from roads. Surface erosion is a major cause of salmonid abundance because it causes water impairments from elevated sediment flows (Beschta et al., 2004). By avoiding using structures and new road construction near stream areas will decrease runoff and sediment flow.

3.3.4 Restrict postfire logging

It is recommended that salvage logging should retain at least 50% of standing dead trees in each diameter class because there are at least 96 wildlife species are dependent on the snags in the forest (Beschta et al., 1995 and 2004). For example, hollow trees with dbh greater than 51 cm are valuable for animal shelter, roosting and hunting (Beschta et al., 2004). In addition, the spread of wildfire is dependent on the finer fuels such as grasses, scrub and tree foliage rather than large trees (Beschta et al., 2004). Therefore, postfire logging will not prevent the reoccurrence of wildfires. If salvage logging must occur, use of cable system yarding can reduce soil disturbance and compaction (Beschta et al., 2004). By restricting postfire logging, we can retain wildlife habitat and reduce soil erosion.

4.0 Conclusion

Wildfire can impact drinking water quality by the deposition of nutrients, total suspended solids, and fire retardant chemicals and change in temperature and pH. The severity of fire depends on these factors as well as the topography, frequency, spatial extent of burning, and amount of available fuel on site. After fire has occurred, we can implement several rehabilitation options such as banning exotic vegetation, controlling livestock grazing, avoiding building operations, and restricting postfire logging.

Wild fires are a critical factor in promoting biological diversity. For example, the large fire that occurred in Yellowstone National Park in 1988, promoted the growth of lodgepole pine. The reproduction of lodgepole pine is strongly dependent on the serotiny of the seeds (Baskin, 1999). At high serotiny sites, high seedling growth density is produced (Baskin, 1999). After high severity fire has occurred, seedling densities increased 4 to 24 times higher that in moderately burned sites (Baskin, 1999). Natural distrubances such as forest fires can be beneficial for promoting pine reproduction.

On average from 1998 to 2008, 42.6% of forest fires were caused by human activities (British Columbia Ministry of Forest and Range). People-caused fires include escaped fires from backyard burning, grass fires, careless use of campfires, and arson (British Columbia Ministry of Forest and Range). The Ministry of Forest and Range has simple recommendations for preventing forest fires, such as do not burn in windy conditions, don't discard smoking materials, and prevent equipment from igniting sparks through exhaust pipes. Paying attention to details can help reduce almost half of the occurrence of forest fires.

Work Cited

Backer, D. M., Jensen, S. E., & McPherson, G. R. (2004). Impacts of fire-suppression activities on natural communities: wildfire and conservation in the western United States. *Conservation Biology , 18*, 937-946.

Barro, S. &. (1987). *Use of ryegrass seeding as an emergency revegetation measure in chaparral ecosystem.* Berkeley, California: U.S. Department of Agriculture Forest Service.

Baskin, Y. (1999). Yellowstone fires: a decade later. *BioScience , 49*, 93-97.

Belsky, A., Matzke, A., & Uselman, S. (1999). Survey of livestock influences on stream and riparian ecosystems in the western United States. *64(6)*, 419-431.

Beschta, R. L., Rhodes, J. J., Kauffman, J., Gresswell, R. E., Minshall, G., Harr, J. R., et al. (2004). Postfire management on forested public lands of the western United States. *Conservation Biology* , pp. 957-967.

Beschta, R., Frissell, C., Gresswell, R., Hauer, R., Larr, J., Marshall, G., et al. (1995). *Wildfire and salvage logging: recommendations for ecologically sound post-fire salvage logging and other post-fire treatments on federal lands in the west.* Retrieved January 25, 2010, from Pacific Rivers Council: http://pacificrivers.org/science-research/resources-publications/wildfire-and-salvage-logging-the-beschta-report

Binkley, D., Burnham, H., & Allen, H. (1999). Water quality impacts of foresty fertilization with nitrogen and phosphorus. *Forest ecology and management , 121*, 191-213.

Bladon, K. D., Silins, U., Wagner, M. J., Stone, M., Emelko, M. B., & Mendoza, C. A. (2008). Wildfire impacts on nitrogen concentration and production from headwater streams in southern Alberta's Rocky Mountains. *Canadian Journal of Forest Research , 38 (9)*, pp. 2359 - 2371.

British Columbia Environmental Protection Division. (2006). *British Columbia approved water quality guidelines*. Retrieved April 12, 2010, from http://www.env.gov.bc.ca/wat/wq/BCguidelines/approv_wq_guide/approved.html#1

British Columbia Ministry of Environement. (2010). *Guidelines for Canadian Drinking Water Quality*. Retrieved November 29, 2009, from http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/sum_guide-res_recom/index-eng.php

British Columbia Ministry of Forest and Range. (n.d.). *Fire Average*. Retrieved November 25, 2009, from http://bcwildfire.ca/History/average.htm

British Columbia Ministry of Forest and Range. (n.d.). *Help prevent wildfire*. Retrieved April 6, 2010, from http://bcwildfire.ca/Prevention/prevent.htm

Buck, R., S., R., A.K, C., Baucke, F., Brett, C., Camoes, M., et al. (2001). *The Measurement of pH - Definition, Standards and Procedures.* A proposal to revise the current IUPAC 1985.

Chanasyk, D., Whitson, I., Mapfumo, E., Burke, J., & Prepas, E. (2003). The impacts of forest harvest and wildfire on soils and hydrology in temperate forests: A baseline to develop hypotheses for the Boreal Plain. *Journal of Environment Engineering and Science , 2*, 51-62.

Crouch, R. L., Timmenga, H. J., Barber, T. R., & Fuchsman, P. C. (2005). Post-fire surface water quality: Comparison of fire retardant versus wildifre-related effects. *Chemosphere , 62*, 874-889.

Dissmeyer, G. (2000). *Drinking water quality from forests and grasslands.* Asheville N.C: U.S. Dept. Agric. For. Serv.

McCullough, D. A. (1999). *A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to chinook salmon.* Seattle, Washington: U.S. Environmental Protection Agency.

McKean, C., & Huggins, B. (1991). *Ambient water quality for pH.* Victoria BC: B.C. Min. Envrion, Water Manage.

Mclver, J., & Starr, L. (2000). *Environmental effects of postfire logging: literature review and annotated bibilography.* Portland, Oregon: U.S. Department of Agriculture Forest Service.

Neary, D. G., Gottfried, G. J., DeBano, L. F., & Tecle, A. (2003). Impacts of fire on watershed resources. *Journal of the Arizona-Nevada Academy of Science , 35*, pp. 23-41.

Pike, R., Feller, M., Stednick, J., Rieberge, K., & Carver, M. (2009). Chapter 12 - Water Quality and Forest Management [Draft]. *Compendium of Forestry Hydrology and Geomorphology in British Columbia* . Victoria: B.C. Ministry of Forest and Range Research Branch.

Ranalli, A. J. (2004). *A Summary of the Scientific Literature on the Effects of Fire on the Concentraion of Nutrients in Surface Waters.* U.S. Department of the Interior. U.S. Geological Survey.

Silins, U., Stone, M., Emelko, M. E., & Bladon, K. D. (2009). Sediment production following severe wildfire and post-fire salvage logging in the Rocky Mountain headwaters of the Oldman River Basin, Alberta. *Catena , 79*, 189-197.

Stark, N. (1977). Fire and nutrient cycling in a Douglas-fir/Larch Forest. *58*, 16-30.

Wells, C., Campbell, L. D., Lewis, C., Fredriksen, R., Franklin, E., & Forelich, R. (1979). *Effects of fire on soil: a state-of-knowledge review.* Washington, D.C.: U.S. Department of Agriculture Forest Service.

Wetzel, R. (2001). *Limnology: lake and river ecosystems.* New York: Academic Press.

Zedler, P., Gautier, C., McMaster, G., & Gregory, S. (1983). Vegetation change in response to extreme events: the effect of a short interval between fires in California chaparral and coastal scrubs. *Ecology , 64*, pp. 809-818.

Advisors

Primary Advisor: Dan Moore

Secondary Advisor: Younes Alila