Effects of forest fire on watershed ecosystem

by

Chenxi Tao

FACULTY OF NATURAL RESOURCES MANAGEMENT
LAKEHEAD UNIVERSITY
THUNDER BAY, ONTARIO

September 2019

Effects of forest fire on watershed ecosystem

by

Chenxi Tao

An Undergraduate Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of
Honours Bachelor of Science in Forestry

Faculty of Natural Resources Management

Lakehead University

September 2019

----------------------------------	---------------------------------
Dr. Jian Wang	Dr. Mathew Leitch
Major Advisor	Second Reader

LIBRARY RIGHTS STATEMENT

In presenting this thesis in partial fulfillment of the requirements for the HBScF degree at Lakehead University in Thunder Bay, I agree that the University will make it freely available for inspection.

This thesis is made available by my authority solely for the purpose of private study and may not be copied or reproduces in whole or in part (except as permitted by the Copyright Laws) without my written authority.

Date: __________April 14th, 2020_________

A CAUTION TO THE READER

This HBScF thesis has been through a semi-formal process of review and comment by at least two faculty members. It is made available for loan by the Faculty of Natural Resources Management for the purpose of advancing the practice of professional and scientific forestry.

The reader should be aware that opinions and conclusions expressed in this document ae those of the student and do not necessarily reflect the opinions of the thesis supervisor, the faculty or of Lakehead University.

MAJOR ADVISOR COMMENTS

ABSTRACT

Tao, Chenxi. 2020. Effects of forest fire on watershed ecosystem. 65pp.

Keywords: forest fire; watershed; hydrologic ecosystem; soil water storage capacity; runoff; restoration; climate change

Global warming has increased the frequency of forest fires and droughts, which have had a number of effects on the hydrologic ecosystems of watersheds`. Therefore, the influence of forest fires on forest watersheds and the problem of late restoration are worth studying. The case studies from different regions of the world about how forest fires affect the hydrological process by consuming plant canopy and waste, affecting soil porosity and affecting organic matter of the soil are discussed in this paper. The effects of forest fire on soil permeability and soil water storage are studied by observing soil moisture and matrix potential. A rainfall-runoff model is established to analyze the comprehensive effect of forest fire and climate change on flooding. The results show that forest fires have an obvious regulating effect on watershed. Mineralization and deposition of soil organic matter, interruption of vegetation root absorption and loss of crown shade will further affect water quality. Additionally climate change will aggravate the erosion of watersheds by forest fires. At the same time, managing forest fires can increase landscape heterogeneity. The study concludes that forest fire is a key factor affecting water resources. At the same time, the impact of forest fires on watersheds varies with the degree of burning. It can be seen that forest fires play a crucial role in guiding the hydrological regulation and restoration of the watershed.

COTENTS

TABLES AND FIGURES

ACKNOWLEDGEMENTS

I would like to thank my thesis advisor Dr. Jian Wang for aiding me in the creation of this project, as well as Dr. Mathew Leitch who helped me throughout this project with any questions I had. I would also like to thank everyone who I have spoken with and consulted with for helping get me involved in this emerging sector and who assisted with this project in any way.

1.0 INTRODUCTION

Forest fire, as an ecological factor of the forest ecosystem, often acts on the forest ecosystem (Hu et al., 1990). Once the fire is out of human control, it will form forest fire, which spreads and expands freely in the forest land. Forest fire damages the ecological environment, aggravates soil erosion and affects the hydrological process of the river basin. Studies have shown that fires in the northern forests have been frequent in the past 30 years (Westerling et al., 2006). With global warming, earlier snowmelt in the Rockies could further increase the frequency of fires. Forest fire disaster has attracted great attention from all countries in the world, and studies on forest fire and its influence have constantly been emerging, among which the hydrological effect of forest fires is one aspect (Zhou et al., 2013).

The hydrologic characteristics of soil under forest are affected by forest fires. Soil permeability and soil water storage change with the change of soil porosity after the fire. Forest fire changes the interception of forest and redistributes precipitation by consuming plant canopy and waste (Zhou et al., 2013). After the fire, surface evapotranspiration changes, which is related to surface runoff and groundwater. In the burning area of the four-mile canyon fire in Colorado, USA, soil moisture content and matrix potential are indirectly measured at different depths below the soil surface to obtain soil hydrology under the ash layer, while the surface runoff and precipitation can be directly observed (Ebel et al., 2011). There are 77 serious burning sites in the Sierra Nevada (Boisrame et al., 2017). The total measurements are 3300 times, which include oil type, slope, altitude, vegetation coverage, the ratio of annual runoff and precipitation (Boisrame et al., 2017).The Llobregat basin forest in Spain, due to 19 temperature sensors and 22 rain gauges, covers the whole basin, which can obtain the complete time sequence of the basin, to draw fire response after the flood (Versini et al., 2012). Water quality can also be affected after wildfires, with increased concentrations of heavy metals and nutrients and altered organic composition (Smith et al., 2011; Gresswell, 1999; Emelko et al., 2011). In a northern forest catchment of the experimental lake district of northwest Ontario, wildfires lead to increased concentrations of alkaline cations and strong acid anions in rivers (Bayley et al., 1992). In five streams in the blue ridge mountains of South Carolina, basins with different burning and fertilization levels were monitored for 12 months to obtain different ion concentrations (Neary et al., 1982). After the rodeo-chediski forest fire in 2002, the station re-monitored the flow conditions, soil properties, and sediment transport after the fires of different degrees, and erosion and deposition in the heavily burned watershed increased (Gottfried et al., 2003). In order to explore the forest fire influence mechanism on the hydrological process and provide guidance for hydrological restoration in the later stage, the influence mechanism of forest fires on forest watersheds and the problem of restoration in the later stage are worth studying.

1.1. objective

The objective of this paper is to research the regulation effect of forest fire on watersheds. By discussing the influence of forest fire on soil hydrological characteristics, precipitation distribution, surface evapotranspiration, runoff, and water quality, this paper provides guidance for hydrological restoration in the later stage and summarizes the importance of fire in the forest ecosystem. Fire is a physicochemical process that results from the interaction of intensity, climate, slope, topography, soil, and area. Therefore, the impact on water resources is continuous. Much information will be incorporated into this study to describe the scope of these effects. This paper also aims to briefly summarize the research status of fire impact on watershed resources in different regions of the world. The primary resources concerned are vegetation, soil, flow, and water quality.

1.2. Hypothesis

A forest fire has a noticeable regulating effect on watersheds. Catastrophic fires caused or intensified by natural events (drought, insect outbreaks, lightning, etc.), will cause severe damage to watershed resources. At the same time, managing forest fires can increase landscape heterogeneity.

2.0 LITERATURE REVIEW

Fire is a very common natural phenomenon in forest ecology, and in recent years, with global warming and drought, fire occurs frequently. The existence of some forest types depends on the regeneration of competing tree species destroyed by forest fires. However, frequent fires destroy trees and organic fertilizers in the forest and affect the water circulation of forest ecology. As a component factor of the forest ecosystem, forest fire and water are closely related. The effect of forest fire on the water is indirect. The ecological environment of forest vegetation, soil, water circulation, and water quality will be changed after a forest fire.

2.1 Effects of forest fire on an interception

Plant canopy and ground cover have important interception effects on rainwater. The forest redistributes precipitation through the forest canopy and waste layer, which can reduce the impact of rain on soil, reduce surface runoff and soil erosion, and facilitate water infiltration. Removed rainfall-runoff and trunk through the amount of rain is the forest canopy interception of precipitation, precipitation through loose waste layer for secondary distribution, the final part of the precipitation infiltration into the soil, gradually formed surface runoff (Zhou, 2013). The plant canopy and ground cover layer depend on the action of the interception of rain precipitation intensity, rainfall duration, and leaf surface area volume ratio. If the precipitation intensity is large, the duration is long, and the leaf surface area volume ratio is small, its interception effect is small (Yao and Du, 2002).

After the fire, the canopy of plants is destroyed, especially the waste layer on the surface is destroyed, which leads to the interception of the forest ecosystem reduced and even lost (Zhou, 2013). Due to the spatial heterogeneity of forest fires, the destruction range of forest canopy and waste layer is not uniform, resulting in a difficult determination of interception. The interception changes of forest fires on forest canopy and ground cover layer are different with different burning degrees and burning types. In the burning area of the four-mile canyon fire in Colorado, USA, the rainfall after the forest fire is observed, which can be used to measure the runoff of forest (Ebel et al., 2011).

2.2 Effects of forest fire on soil hydrology characteristics

Good forest soil physical structure with high porosity, has a strong water permeability and water holding capacity. After the forest fire, surface vegetation, waste layer, and humus layer will be seriously damaged, and the chemical and physical properties of the soil will change, affecting the permeability of the soil and soil water storage (Zhou et al,, 2013).

2.2.1 Effects of forest fire on soil permeability

Good soil permeability is a critical characteristic of forest hydrology, which is related to surface runoff, groundwater recharge and soil erosion. Due to the influence of waste layer, tree roots, and special undergrowth organisms, the soil surface of forest ecosystem is rich in organic matter and humus, forming a good soil agglomeration structure and pore condition, which is conducive to water infiltration. With the deepening of soil layer, the root density decreased, the content of soil organic matter gradually decreased, the porosity of soil decreased, the soil capacity increased gradually, and the permeability of soil decreased. Generally speaking, after the high intensity fire, waste layer was burned down and the organic matter content was significantly reduced. For example, Fernandez et al. (1997) compared the organic carbon content in the surface soil with no fire and high intensity forest fire, and found that the organic carbon content in the area with high intensity fire was significantly lower than that in the area without fire (Fernandez et al., 1997). Organic matter is an essential material to form soil structure. After fire, the content of organic matter in the soil top layer decreases, resulting in the decrease of soil stability. Under the splashing erosion of raindrops in the later stage, the soil is more likely to disintegrate, and the scattered particles fill the pores on the soil surface and form crust on the soil surface under the erosion of rain, leading to poor soil permeability (Zhou et al., 2013). According to the survey conducted in the sandy loam forest of Illinois oak forest, the water infiltration after fire is only 1/3 of that before burning (Horton and Kraebel, 1955).

In addition, soil hydroscopicity is also an important factor affecting soil permeability. After organic decomposition, water-repellent organic matter in soil is formed, which makes the soil particles and moisture particles repel each other, leading to the weakening of soil water infiltration performance. The smaller the soil moisture content is, the more water-repellent the soil is (Mataix-Solera et al., 2011).

2.2.2 Effect of forest fire on soil water storage

When the soil thickness is constant, the smaller the soil bulk density is, the larger the porosity is, and the larger the water storage capacity is (Gerrits, 2010). The storage capacity of forest soil is mainly determined by the non-capillary soil porosity. The forest soil structure is loose due to the waste layer on the forest surface and the intricate root system in the soil system. Vegetation coverage has a great impact on soil water holding capacity. Forest fire destroys waste layer and humus layer, seriously affects the water storage capacity of soil surface layer, and reduces the water storage capacity of soil (Kozolows, 1974). The experimental study in Greater Khingan Mountains shows that the decrease of waste layer and soil moisture content leads to the increase of soil bulk density and the decrease of water stable aggregate content. Waste layer plays a very important role in protecting forest soil, maintaining the moisture content of soil, ensuring the stability of soil temperature and preventing the erosion and loss of forest soil (Song et al., 2015). An analysis of soil in the burning area of the four-mile canyon fire in Colorado, USA, found that the size and time delay of the burned soil were significantly reduced compared to the unburned soil, indicating a significant decrease in soil infiltration in the burning area. In the process of rainfall, the soil moisture content at the top 3 cm of the soil after fire showed a significant small scale (5-10 cm) spatial change, while that of the unburned soil showed no change. The soil infiltration capacity in October 12 and 22 is close to zero because of there is a storm with heavy rain (Ebel et al., 2011). However, some studies have pointed out that the net transpiration of plants after fire and the evaporation decreased after the structural damage of soil after fire. Therefore, the water content of soil after fire is higher than that before fire. In a forest area in Oregon, the water content of soil increased by 12.7cm after the fire within a soil layer of 120cm. After 3 consecutive years of observation, it was concluded that it would take about 5 years to recover to the original level (Chandler, 1983).

2.3 Effects of forest fire on surface evapotranspiration and runoff

2.3.1 Effects of forest fire on surface evapotranspiration

For watersheds without interference from human activities, evapotranspiration is the main component of water loss. Evapotranspiration in forest watershed mainly includes interception evaporation, vegetation transpiration and soil evaporation. Generally speaking, evapotranspiration in watershed with good vegetation coverage is dominated by interception evaporation and vegetation transpiration, followed by soil evaporation (Li et al., 2011). However, forest fire destroys a large amount of vegetation, which directly leads to the sharp reduction or loss of interception evaporation and vegetation transpiration (Cornish and Vertessy, 2001). The evapotranspiration of forest watershed was changed from vegetation transpiration to soil evaporation. After the fire, with the growth and recovery of vegetation, evapotranspiration in the watershed gradually returns to the level before the fire, but this is a long-term process. On the other hand, the fire reduced the stand density and improved the light conditions in the forest, and the forest was rich in nutrients after fire, which was conducive to the germination and growth of plant seeds (Zhou et al., 2013).

The change of evapotranspiration in the forest watershed is closely related to the severity of the fire and the climatic conditions. The more serious the fire, the larger the area of vegetation damage and the more drastic the evapotranspiration in the watershed. Climatic conditions are also important factors affecting changes in watershed evapotranspiration. The water supply conditions in humid climate areas are sufficient, and evapotranspiration of the watershed is mainly determined by evapotranspiration capacity, and vegetation growth does not necessarily cause significant changes in actual evapotranspiration; While in arid areas, evapotranspiration of watershed is mainly determined by surface water supply, and the growth of vegetation leads to the increase of evapotranspiration (Cornish and Vertessy, 2001).

2.3.2 Effects of forest fire on runoff

Forest fires affect the runoff of watershed by affecting evapotranspiration, Surface evapotranspiration changes, which is related to surface runoff and groundwater.

Forest fire combustion reduces vegetation interception, transpiration and water storage of ground cover, so that more water penetrates the soil and surface runoff increases after forest fire combustion. A series of responses will occur in the watershed after the fire: increased river flow, early and violent flood peak, increased risk of heavy rain and river flooding, etc. Located in the northern cold temperate zone, the Greater Khingan Mountains, with single vegetation and shallow soil, experienced a significant increase in annual runoff after the huge forest fire (Cai et al., 1995). The regulation ability of a forest to water circulation is weakened after fire, and the change of runoff is more dependent on rainfall (Cai et al., 1995). After the fire, especially the large area fire, the water flow of the downstream river increased obviously. In the Llobregat river basin of Spain in the Mediterranean region, an analysis of mountain torrents' response after a forest fire was conducted. The study shows that forest fire has a crucial impact on vegetation destruction and soil hydrological property change: after fire, the peak flood flow increased by 40%, the runoff rate increased to 30%, and the low peak time decreased by 20 minutes (Versini et al., 2013). It shows that the frequency of flood changes significantly after fire and forest fire has an obvious regulating effect on the hydrological response of watershed scale (Versini et al., 2013). In the face of global warming and drought in the west, Yosemite National Park and Illilouette Creek Basin have experienced 40 years of effective wildfire management, showing significant increases in humidity in areas where fires lead to a transition from forest to dense grassland (Boisrame et al., 2017). Since 1973, the runoff ratio (annual runoff to precipitation ratio) in the watershed appears to have increased or stabilized, while the runoff ratio in nearby unburned watersheds has decreased (Boisrame et al., 2017). Managing wildfires seems to increase landscape heterogeneity.

Any natural (unplanned) disturbance that causes a significant change in forest density, structure or composition can cause a significant change in water balance. The increase in the total amount of water produced by severe wildfires is approximately equivalent to that caused by clearing-down and, in catchment terms, should be substantially proportional to the portion of the forest cover destroyed. If waste and organic layer are seriously burned, its influence on peak discharge is obvious. It has been found that even planned fires for harvesting residues can increase surface runoff and erosion. Intense fires often increase the discharge of residues during floods (Yao and Du, 2002).

The influence of forest fire on watershed water yield depends on the response of vegetation to fire in forest ecosystem. Forest fires mainly affect the water yield of the watersheds through the following aspects: first, the degree of forest interference by fire. It mainly refers to the range of forest stream affected by fire and the intensity of fire. When the affected area of forest watershed is less than 20%, forest fire has no obvious influence on the runoff in the watershed (Bosch and Hewlett, 1982). Secondly, the ecological response of vegetation to fire. It mainly refers to the restoration of forest canopy from seed regeneration or from trees that have not been burned to death. Compared with the restoration of damaged trees, the restoration of vegetation by seed germination and growth is a long-term process, which has a great influence on the yield of watershed water. Third, the time before the fire. After the fire, vegetation through regeneration or recover gradually formed a new forest ecological system. The time from the fire will have an impact on to the formation of a new forest ecosystem such as the age of new trees, the density of new forests, and the growth of new forests. These factors reflect the water consumption of new forests. Finally, the rate of natural thinning and aging of forests. With the gradual restoration of vegetation, survival of the fittest among trees gradually reaches a new ecological system balance. The rate of natural thinning and aging of forest affects the time of water yield restoration before fire (Zhou, 2013).

The influence of forest fire on runoff will accompany the vegetation restoration stage, so it is a long-term process. It can be divided into three stages: the first stage, short-term (2-5 years) runoff after fire increased. The fire destroyed the forest canopy and ground waste layer, resulting in the reduction of interception and evapotranspiration. At the same time, the chemical and physical properties of the soil were changed, which ultimately increased the water yield in the watershed. In the second stage, 20-40 years after the fire, with the gradual restoration of vegetation, the water yield in the basin gradually reduced to the minimum value. In the fire, seeds falling into the soil grew and developed under sufficient light and nutrients, and vegetation competed for nutrients and rapidly grew, canopy interception and transpiration gradually increased, and vegetation water consumption gradually reached the peak. In the third stage, runoff increased and gradually recovered to the relative equilibrium stage before fire disaster. At this stage, the forest canopy has basically developed completely and started to age. The hierarchical structure in the natural sparse forest of vegetation has been formed. The evapotranspiration in the watershed has gradually decreased to the pre-fire equilibrium state, and the runoff in the watersheds has increased and reached a new equilibrium under the condition of average precipitation (Neary et al., 2005).

As a long and continuous natural disturbance, fire has a great influence on the forest ecosystem in southwest China. Fire is a physicochemical process that results from the interaction of intensity, climate, slope, topography, soil and area (DeBano et al., 1998). Therefore, the impact on water resources is continuous. The greater the fire intensity, the more serious the impact on water resources. Intensity is the result of climate, temperature, slope, topography, soil and watershed size. The combination of fire intensity and duration produces resource impacts, which we then classify as fire severity (low, medium, high). The increase in peak flow depends largely on the burned area, watershed characteristics, and fire severity. Small areas on flat terrain are subject to regulated fires and have little impact on water resources. After a large area of steep land is burned by a mountain fire, the watershed tends to produce a significant response (Neary et al., 2003).

In general, the influence of forest fire on the hydrological process of the watershed is closely related to forest type, the severity of fire, and precipitation characteristics. Forest fires disturb the stability of the forest ecosystem, break the ecological environment, and affect the water circulation in the flow area. The study on the hydrological response of forest fire is of great significance to vegetation recovery after a disaster and the planning and utilization of water resources in the watershed.

2.4. Effects of forest fires on river siltation and river water quality

Forest fires can affect river deposits and water quality. The size of fire area, the intensity of fire, soil type, size of river and its geographical position all have a great influence on river sedimentation and river water quality (Zhou, 2013).

2.4.1 Effects of forest fires on river siltation

After fire, forest vegetation is destroyed, the function of forest water source is reduced or disappeared, and surface runoff is increased, thus increasing sediment deposition and river flow volume downstream. Increased river discharge accelerates and amplifies the impact of river water on the banks and also increases river deposition, sometimes more than that from surface erosion (Yao and Du, 2002). After the rodeo-chediski forest fire in 2002, the station re-monitored the flow conditions, soil properties and sediment transport after the fires of different degrees. The intensity and severity of fires vary from region to region in the watershed. Analysis of monitored flow conditions, scour and silt processes, and other field hydrological features indicated an increase in erosion and deposition in heavily burned basins (Gottfried et al., 2003).

2.4.2 Effects of forest fires on river water quality

Surface runoff, soil erosion, soil landslide, dry erosion and channel drift caused by the destruction of vegetation after fire all affect the change of water quality in the lower reaches of the river to different degrees. River turbidity is one of the important indexes of river water quality (Yao and Du, 2002). Increased concentrations of heavy metals and nutrients, and altered organic composition has been reported (Gresswell, 1999; Emelko et al., 2011). In a boreal forest catchment in northwestern Ontario's experimental lake district, wildfires have resulted in increased concentrations of strong alkaline cations and acid anions in rivers. The drought produced a weaker response to fire which cause high sulfate concentrations and reduced river pH. Warming increases the frequency of droughts and fires, exacerbating the loss of S and H^+ (Bayley et al., 1992).

The influence of fire on the water quality of downstream rivers is also manifested in the change of chemical components in the river water, especially the change of chemical substances such as nitrogen (N), potassium (K), phosphorus (P), magnesium (Mg), calcium (Ca), and sodium (Na). There is nitrate nitrogen, ammonium nitrogen and organic nitrogen in the river (Neary and Currier, 1982). The increase of nitrogen compounds in the river flow after burning indicates that there is a large amount of nitrogen loss in the burning area, which does not pose a serious threat to the productivity of the burning area, but it will have some impact (Neary and Currier, 1982). Phosphorus in soil solutions, rivers, lakes, etc., exists mainly in two forms: one is inorganic phosphorus (orthophosphate), the other is organic phosphorus (Neary and Currier, 1982). The amount of phosphorus in phosphate is usually thought of as the total amount of phosphorus. After fire, the content of total phosphorus in river water increased. However, the increased amount did not cause water quality changes in rivers and lakes (Neary and Currier, 1982). Bicarbonate ion is the main anion in soil solution and the best product of plant root absorption. After the fire, the content of hydrogen carbonate in the soil and downstream in the river increased (Grren, 1981). Five streams in the blue ridge mountains of South Carolina were monitored for 12 months after being affected by fires of varying severity. Differences in no3-n, nh4-n, po4-p, Na, K, Ca and Mg concentrations were attributed to fires or subsequent watershed improvement operations (Neary and Currier, 1982). The concentration of no3-n increased the most (peak value was 0.394 mg/l). The levels of ammonia nitrogen, no3-n and po4-p increased mainly during heavy rain. Sodium, potassium, calcium and magnesium concentrations were 12 to 82 % higher than background levels during most of the monitoring period. The results showed that the detected water quality changed, but did not decrease the value of the river as a potential source of drinking water (Neary and Currier, 1982).

3.0 METHODS AND MATERIALS

The published experimental methods of forest land under different geological forms and fire intensity were integrated and compared to study the effects of forest fire on soil hydrological characteristics, precipitation distribution, surface evapotranspiration, runoff, and water quality in this study. This part includes five different regions to describe the impact of forest fire on hydrological characteristics and briefly describes the research methods from different areas of the world on the present situation of forest watershed after burning. In the subsequent data analysis, ANOVA was used to analyze the impact of fire on hydrological characteristics under different conditions. SPSS and Excel software were used in this study for data analysis. The following is the original data source achieved methods from the literature.

3.1. Study on soil hydrological characteristics after fire

3.1.1 Four mile canyon, Colorado, USA

3.1.1.1 Soil hydrological characteristics

Eight days after the four-mile canyon forest fire in Colorado, Brian et al. (2012) installed instruments in the burned and unburned areas to measure soil samples and precipitation. It lasted from September 14, 2010, to November 8, 2010.

Periodic measurements are made on two given areas, the burned area, and the unburned area. Every other day or two, at a depth of 0-3 cm, collect a sample of the burned and unburned areas. The soil water content of these samples was estimated by thermogravimetry Q (Topp and Ferre, 2002). Thermogravimetric measurements were averaged over four repeated samples (60 g each). The sample was weighted to within 0.001g with an estimated error of 60.005g or < 0.01%. Volume density is calculated by dry weight and core volume per sample (Ebel et al., 2012).

A tunnel was dug in the two burning and unburned sample plots, and the soil was filled up after an underground sensor was inserted. The time resolution of the sensor was 1 minute, and the soil moisture content and temperature were measured at 5cm, 10cm, and 15cm depths. Similarly, soil temperature and humidity sensors were installed in tunnels dug at 3cm and 6cm of the soil depth in the combustion sample site, and 5cm of the soil depth in the unburned sample site, and the soil was backfilled. Estimation of matrix potential was calculated using the kelvin equation (Koorevaar et al., 1983). Koorevaar equation is applicable to meager matrix potential after the fire (Ebel et al., 2012).

3.1.1.2 Precipitation and runoff

In the burned and unburned areas, the local rainfall was continuously measured using an automatic tipping bucket rain gauge with a tip of 0.254 mm. The intensity of precipitation over a period of 5 minutes was estimated by linear interpolation. A 3-inch par-shall flume was installed in the catchment of the burned sample site to measure surface runoff emissions. The ultrasonic sensor monitors the depth of water in the tank at a time resolution of 10 s. The sink is cleaned 2-3 times a week to remove sediment deposited by previous runoff (Ebel et al., 2012).

3.1.2 Greater Khingan Mountains

The study area is located in the Huzhong region of the Greater Khingan Mountains, with a continental monsoon climate of cold temperate zone, large temperature difference between day and night, 746 mm average annual precipitation, and coniferous forest vegetation in cold temperate zone. These characteristics are similar to the experimental land in Colorado. In the late spring and early summer of 2010, part of the forest land was hit by forest fire, and the vegetation layer basically turned to ashes. Almost all the vegetation layer of the forest land was burned, which was a severe fire (Song et al., 2015).

The typical sections were selected and 40 m×40 m square plots were set respectively in the severely burned areas and unburned areas in the same slope position and slope direction. Obtain 121 plots each in the burned area and the control area. Samples of 0-5cm were collected in the typical sunny days after the fire was completely extinguished and after the heavy rain. Meanwhile, the habitat factors in soil were monitored by soil detector. For the obtained data, SPSS software paired sample T-test was used to analyze whether there were significant differences between the data (Song et al., 2015).

3.2. Study on runoff after fire

3.2.1 The Sierra Nevada

3.2.1.1 Soil Moisture Measurements

From 2014 to 2015, soil hydrology in Yosemite National Park and Illilouette Creek Basin in Nevada was comprehensively monitored after a forest fire. More than 3,300 measurements were made at more than 70 sites, including burn severity, ignition time, soil type, slope, aspect ratio, elevation, and vegetation cover. Each site made one to five repeated measurements using the Hydrosense II probe (Campbell Scientific 2015) and the 12 cm time-domain reflectometer (TDR). All measurements were recorded with volumetric water content (VWC), which represents the proportion of soil matrix composed of water in total volume (Boisrame et al., 2017).

Random forest model was used to determine the relationship between soil moisture content and conditions such as vegetation type, uphill area, slope, slope direction, topographic position, topographic humidity, and fire severity (Liaw and Wiener, 2015). The model was run in 1969 and 2012, respectively. The burn time and fire severity were set to 0. The 2012 data were set according to the observed values. Through this set of controlled experiments, the variations of fire and vegetation on forest land under the same climate conditions were obtained (Boisrame et al., 2017).

3.2.1.2 Runoff ratio analysis

Similar to the previous experiment, the precipitation after a period of time series in upper Merced watershed was measured with instruments. The annual runoff ratio is obtained by annual precipitation. By dividing the time series into the period before and after 1973, the trend and change of the annual runoff ratio under the conditions of similar vegetation, area, terrain, and elevation in the two periods can be calculated (Boisrame et al., 2017).

3.2.2 Greater Khingan Mountains

In 1987, a huge fire broke out in the northern part of the Greater Khingan Mountains. This area belongs to the continental monsoon climate in the cold temperate zone, the climate is cold and dry, the daily temperature difference is great. This is similar to the dry climate of Nevada. The local runoff supply is mainly rainwater, and the surface runoff is abundant. The huge fire did great damage to the forest resources. The selected basins are Emuer river and Pangu river, and the burning area of the two basins accounts for 81.5% of the total burning area of the Greater Khingan Mountains. Therefore, the study basins are very representative. Three sample areas were choosen as the research plots, including Pangu stand for unburned basin. The change of flow before and after combustion and the comparative analysis between burnt and unburnt basins were studied by using the method of single basin and double basin. The rainfall-runoff relation was also calculated (Cai et al., 1995).

3.3. Study on water quality after fire

3.3.1 The Experimental Lakes Area in northwestern Ontario

Beginning in June 1971, a weir was installed in the experimental lake area in northwestern Ontario to monitor surface runoff. Samples for chemical analysis were collected once a week to calculate the flow of chemical concentrations and to get a weighted average. Comparative analysis of chemical ion concentrations in the watershed after fires in 1971 and 1980 was calculated (Bayley et al., 1992).

The ph value of the water sample, NO_3-N, dissolved inorganic carbon (DIC), basic cation, $C1^-$ and SO_4^- were analyzed. The difference between the sum of strong acid anions (SO_4^-, CI^-, NO_3-N) and the sum of basic cations (Ca^{++}, K^{+}, Mg^{++}, Na^{+}) were obtained by ANC calculation. The method of Stainton et al. (1977) was used to analyze all ions except sulphate. The sulphate was measured using ion-exchange techniques from 1974 to 1979 (Stainton et al., 1977). Dionex ion chromatography was used for water samples after a fire in 1980 (Bayley et al., 1992).

3.3.2 The Blue Ridge Mountains of South Carolina

A similar method was used to monitor and obtain water samples in the Blue Ridge Mountains of South Carolina. Water samples were collected once a week in five monitored watersheds. Samples were collected monthly after a fire in 1978. The samples were then frozen in 250 ml polypropylene bottles and sent to the Coweeta Hydrological Laboratory for research. The anions and cations in the solution were studied by standard colorimetry and atomic absorption. After filtration, the suspended solids were determined by gravimetric analysis (Neary and Currier, 1982).

Estimate the production of water in the monitoring watershed. The estimated monthly flow is calculated using the procedure recorded in WRENS (USDA FS 1980) to estimate water flow in the watershed over a 12-month period. Repeated experiments were performed to determine the soil, vegetation, geological conditions, and rainfall similar to the Coweeta basin in the burning area of the Blue Ridge Mountains in South Carolina (Neary and Currier, 1982).

4.0 RESULTS

4.1. Study on soil hydrological characteristics after fire

4.1.1 Four-mile canyon, Colorado, USA

4.1.1.1 Thermogravimetric Soil Water Content

The time series of soil moisture in the burned and unburned samples were measured by the thermogravimetric method to obtain the hydrological state before and after precipitation in the four-mile canyon in Colorado, USA (figure 1). A few weeks after combustion, it was measured that the content of soil moisture of the burning sample land was lower than that of the unburned sample land, and the soil of the burning sample land remained in a state of continuous drought (figure 2). On October 12, a broad range of rainfall began to occur in the local area. The precipitation time series on that day was 15 for the burning sample plot and 14.1 for the unburned sample plot. Precipitation has since declined, but rose again on October 20. Ash responds quickly to rainfall. No matter it is light rain, for example, the precipitation was only 2.1 mm on October 18, or after the heavy rain with 15.2 mm on October 12, the ash layer of the burned sample land lost water rapidly by means of drainage or evaporation. The change of water content of the ash layer indicates that the water content increases significantly with the input of precipitation. Unlike the ash layer, the response of the soil to precipitation in the sample land after combustion was delayed (figure 2). On October 12, the rainfall was as high as 15.2 mm, but the soil moisture content of the burning sample was increased on October 20 after lagging for several days. The reason may because that the ash layer produced on the top of the burning soil acts as a buffer, trapping and draining part of the water. Comparatively speaking, the soil of unburned sample land can respond quickly to the water content of precipitation input without the phenomenon of lag. In figure 2, the variation of ash layer data after precipitation is abundant, followed by that of unburned sample plots, and the change of soil water content in burned sample plots is small.

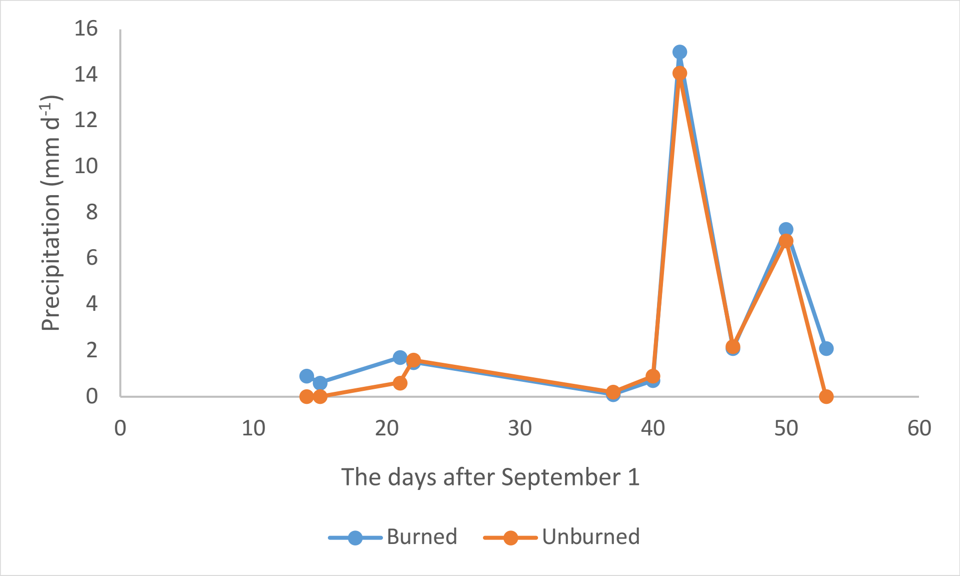

Figure 1. Precipitation time series in burned and unburned areas

Source： Ebel et al., 2012

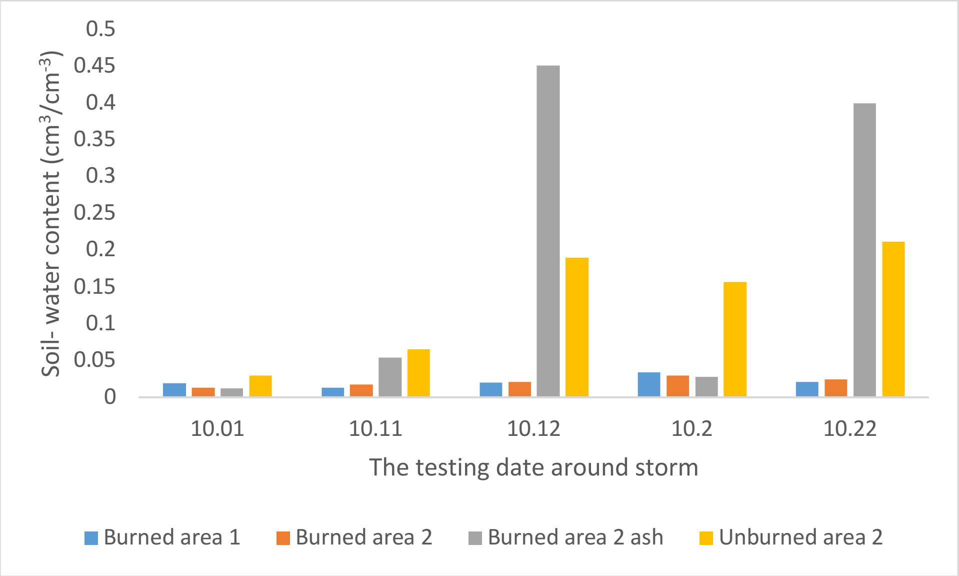

Figure 2. Soil moisture content of thermogravimetric samples before and after October 12th (heavy rain)

Source: Ebel et al., 2012

4.1.1.2 Automated Soil Water Content

An automatic underground sensor was used to detect 1-minute soil moisture content. The results show that a significant difference existed in the response between the combustion sample and the uncombustion sample, and the results are similar to those measured by the thermogravimetric method. Figure 3 shows the change of soil moisture content when the 1-minute sensor is installed in the vertical profile of the soil. After the initial small-scale precipitation in September, the soil moisture content measured at 5cm, 10cm and 15cm varied little. On October 12, there was a 15.2 mm of heavy rain, when the range of the data increased significantly. The soil water content in the three levels of unburned sample plots was more significant than that in the combustion sample plots, especially the soil water content at 5cm and 15cm of the combustion and unburned sample plots varied significantly (figure. 3).

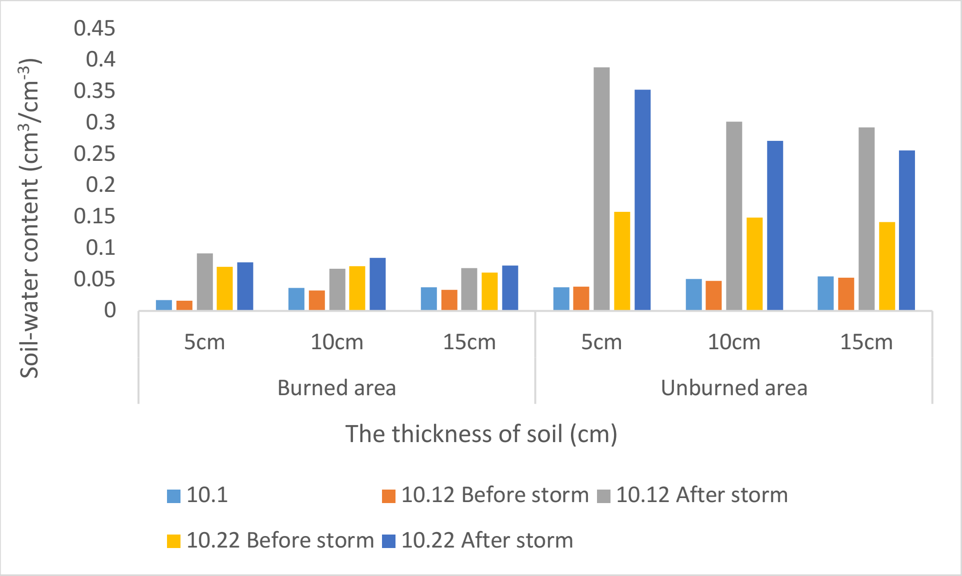

Figure 3. Soil moisture content when the sensor is installed

Source：Ebel et al., 2012

The data after October 12 were mainly observed (table 1, figure 4). After the precipitation of 15.2 mm, the response of the soils in the burned and unburned samples to the larger storm was significantly different. The soil moisture content at the 5 cm depth of increased by 0.076 cm^3, while that at the depth increased by 0.35 cm^3. Before and after the storm on October 22, the soil moisture content increased by 0.007 cm^3 at a depth of 5 cm in the burning sample plots, while that at 5 cm depth in the unburned sample plots increased by 0.196 cm^3. The deeper the soil, the smaller the water content and the less the external influence

Table 1. Volumetric Soil-Water Contents from Thermogravimetric Samples

		10.12 Before the storm （cm^3/cm^3)	10.12 After the storm （cm^3/cm^3)	10.22 Before the storm （cm^3/cm^3)	10.22 After the storm （cm^3/cm^3)
Burned area	5cm	0.016	0.092	0.071	0.078
	10cm	0.033	0.067	0.072	0.085
	15cm	0.034	0.068	0.061	0.073
Unburned area	5cm	0.039	0.389	0.158	0.354
	10cm	0.048	0.303	0.149	0.272
	15cm	0.053	0.293	0.142	0.257

Source：Ebel et al., 2012

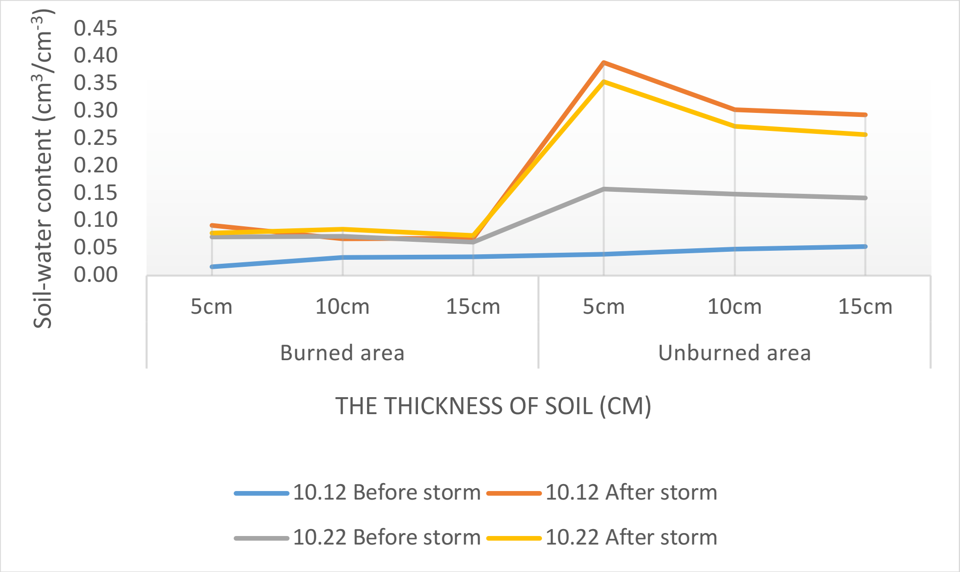

Figure 4. Volumetric Soil-Water Contents from Thermogravimetric Samples

Source： Ebel et al., 2012

Table 2. ANOVA test of moisture content on burned and unburned soil on October 12

Variation of source	SS	df	MS	F	P-value	F crit
Interaction	0. 095761	1	0. 095761	64. 14692	0. 001318	7. 708647
Within	0. 005971	4	0. 001493			
Total	0. 101732	5				

Source: Original data

Table 3. ANOVA test of moisture content on burned and unburned soil on October 22

Variation of source	SS	df	MS	F	P-value	F crit
Interaction	0.069768	1	0.069768	50.50784	0.002071	7.708647
Within	0.005525	4	0.001381			
Total	0.075294	5				

Source: Original data

ANOVA was used to test the influence of burning on soil water content after the storm (table2, table3). After October 12, the P-value was 0.001318, and after October 22, the P-value was 0.002071. The results were all less than 0.05, which was enough to prove that the impact of burning on soil water content was significant.

4.1.2 Greater Khingan Mountains

The analysis by SPSS paired sample T-test showed that the physical and chemical properties of soil were significantly different from those of forest fire (table 4). As can be seen from table 4 and figure 5 to figure 9, the habitat factors of forest soil caused by fire changed significantly ($P<0.01$). Fire removed 93.7% of the waste layer, resulting in a 33.6% decrease in soil moisture content, a 203% increase in average surface temperature at noon, a 22.5% increase in soil bulk density, and a 10% decrease in water stable aggregates at the same time. After a short recovery period 1 year, the habitat factors and so on compared to still exist significant difference ($P < 0.01$), the thickness of waste and water stability decrease aggregate content ratio continues to increase, 95.1% and 39.2%, respectively, the earth's surface at noon have mild rising proportion continues to increase, soil bulk density were 221% and 37.8% respectively, only decreased than patients reduced soil moisture content is 26.0%. After three years' recovery, the soil moisture content decreased to 9.82%, the average surface temperature was 116%, the difference between other factors and the same land continued to increase, the thickness of the waste layer decreased by 97.3%, the soil bulk density increased by 51.4%, and the soil water stability aggregate decreased by 47.8%. Therefore, the effect of fire on soil physical habitat factors is difficult to recover in a short time.

Similarly, fire caused significant changes in the chemical habitat factors of forest soil ($P<0.01$) (table4, figure10). Fire significantly changed the acidity of the soil, increasing the pH value by 14.2%. After 1 year, the soil pH value had a certain recovery, rising by 9.73%. After 3 years of recovery, the soil pH value continued to recover, and the increase rate decreased to 8.92%.

Fire had a significant effect on soil biological habitat factors ($P<0.01$) (table4, figure11). After the fire, the soil microbial biomass carbon decreased by 69.2%. After 1 year and 3 years of recovery, the soil microbial biomass carbon still had significant differences with the control ($P<0.01$), and the decrease rate was 58.0% and 48.3%, respectively. Soil biological habitat factors have not recovered completely within the research time range, indicating that the significant impact of forest fire on soil microorganisms lasts a long time.

Table 4. Changes of 12 soil habitat factors in the burned and unburned area

	2010			2011			2013		
	Unburned area	Burned area	Change rate	Unburned area	Burned area	Change rate	Unburned area	Burned area	Change rate

The dead layer (cm)	10.4	0.66	-93.7	10.4	0.51	-95.1	10.4	0.28	-97.3
Soil moisture content (%)	33.6	22.3	-33.6	38.2	28.3	-26	36.5	32.9	-9.82
Surface temperature (℃)	16.5	50.1	203	14	45.1	221	14.1	30.4	116
Soil weight (g/cm^3)	0.66	0.81	22.5	0.66	0.91	37.8	0.66	1	51.5
Water-stabilized reunion body (%)	84.1	75.7	-10	84.3	51.3	-39.2	84.8	44.2	-47.8
PH	4.61	5.27	14.2	4.57	5.02	9.73	4.47	4.87	8.92
Microbial amount of carbon (mg/kg)	310	98	-69.2	382	265	-58	382	287	-48.3

Source: Song et al., 2015

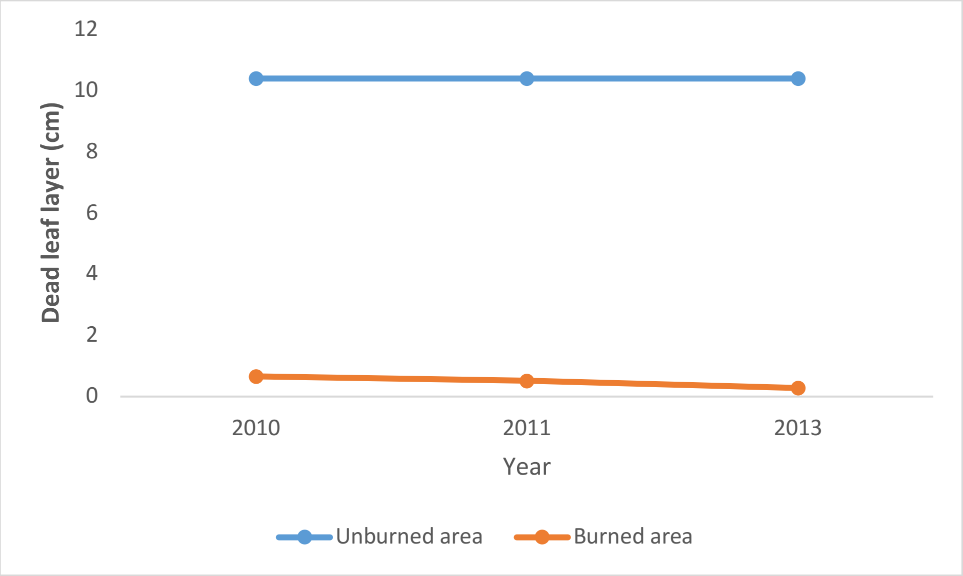

Figure 5. Changes of waste layer factors in burned and unburned area

Source： Song et al., 2015

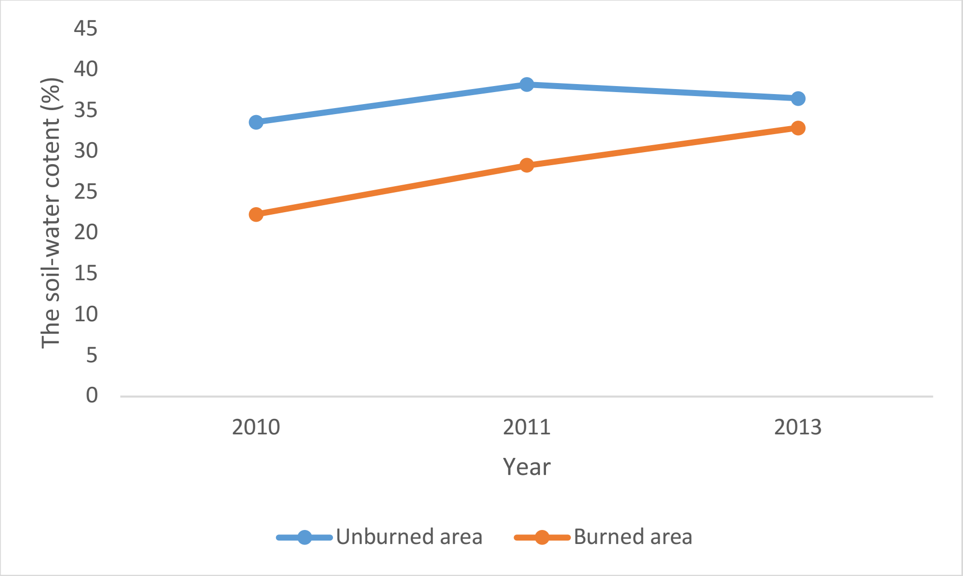

Figure 6. Changes of soil moisture content factors in burned and unburned area

Source： Song et al., 2015

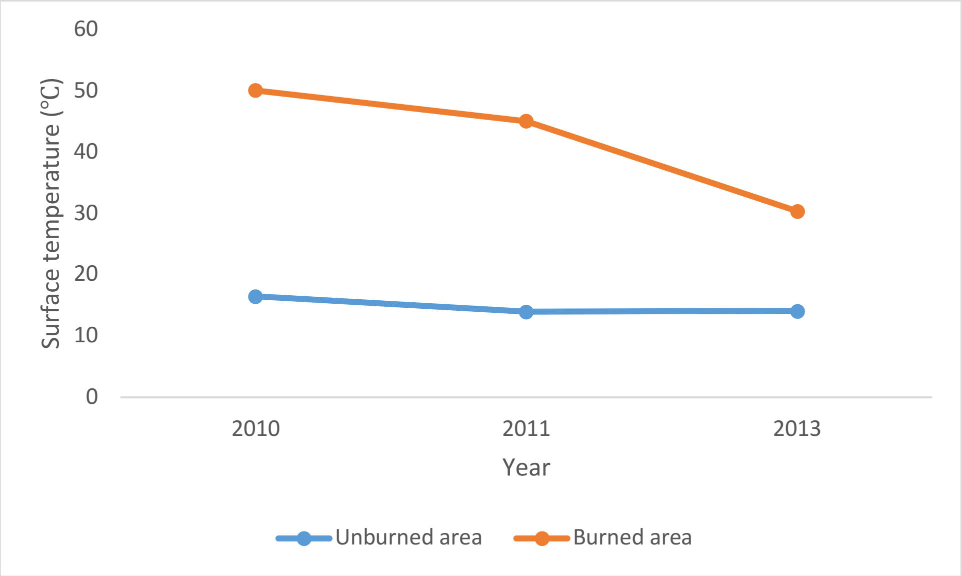

Figure 7. Changes of the surface temperature factors in burned and unburned area

Source： Song et al., 2015

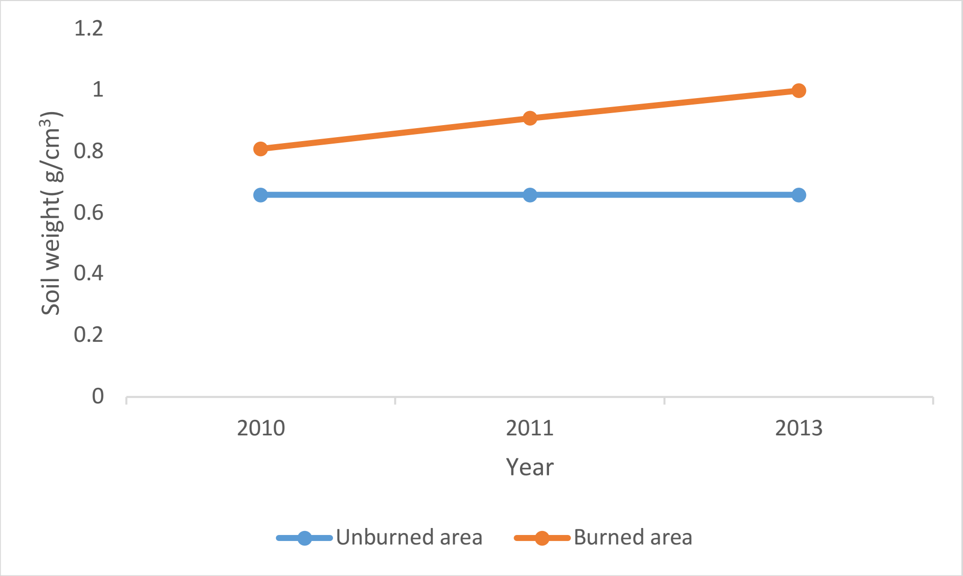

Figure 8. Changes of the soil bulk density factors in burned and unburned area

Source： Song et al., 2015

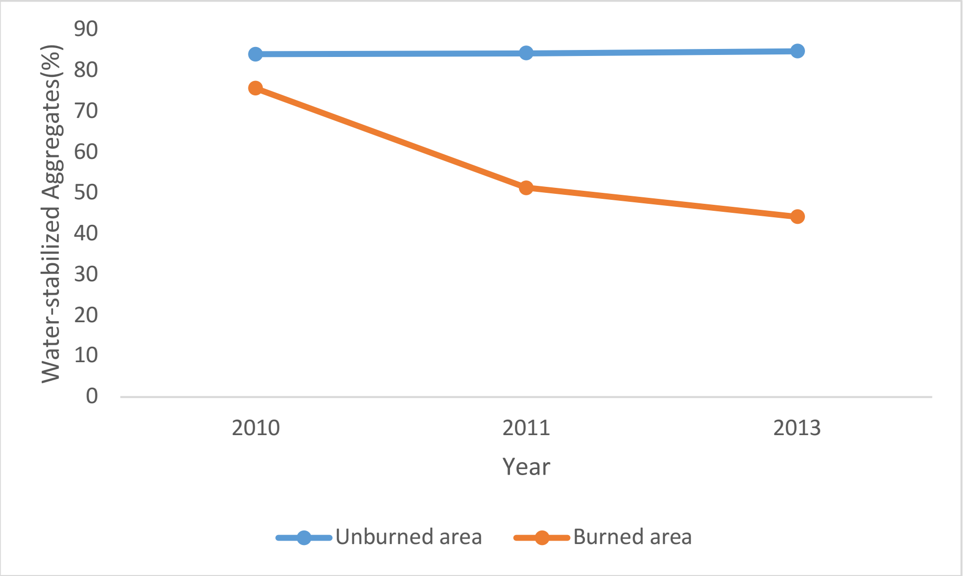

Figure 9. Changes of the water stable aggregates factors in burned and unburned area

Source：Song et al., 2015

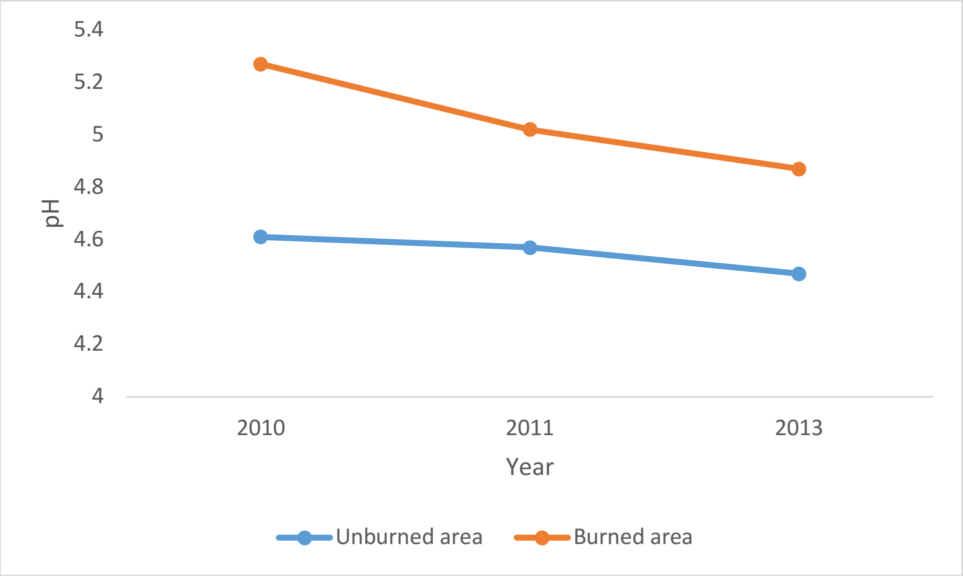

Figure 10. Changes of PH factors in burned and unburned area

Source：Song et al., 2015

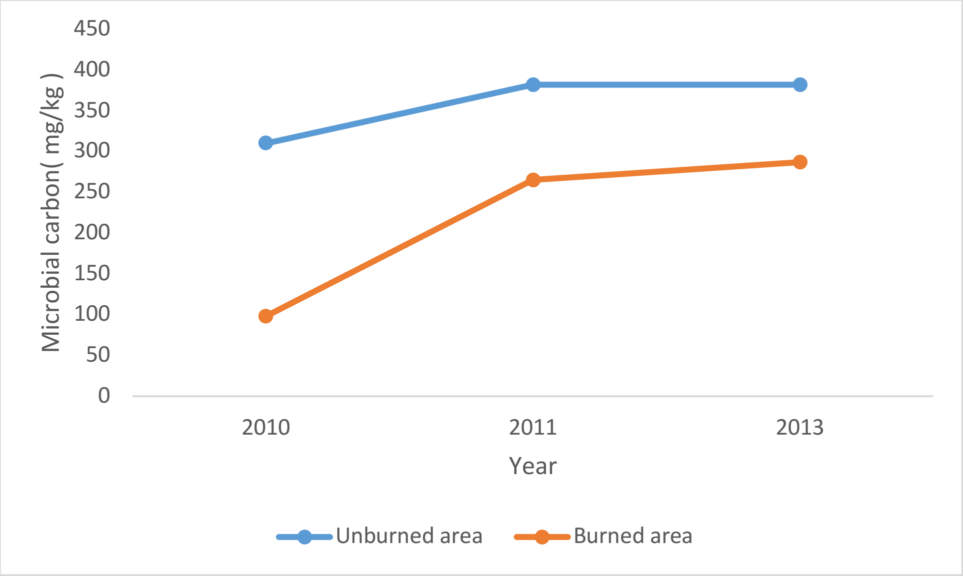

Figure 11. Changes of microbial carbon factors in burned and unburned area

Source：Song et al., 2015

4.2. Study on runoff after fire

4.2.1. The Sierra Nevada

Compared with Upper Merced, basic factors such as watershed, climate, vegetation coverage, and annual precipitation of MF Stanislaus, SF Stanislaus, and Cole Creek were similar (table 5).

Table 5. All watersheds are of Flow, Annual precipitation, Percentage of bured area, watershed area and vegetation coverage.

	Flow （m^3/s）	Annual precipitation (m)	Percentage of burned area	Watershed area (km^2)	Vegetation coverage(%)
Upper Merced	2.9	1.2	23%	453	76
MF Stanislaus	1.8	1.5	0.20%	119	55
SF Stanislaus	1.7	1.6	3.30%	112	88
Cole Creek	0.4	1.5	14.70%	53	91

Source: Boisramé et al., 2017

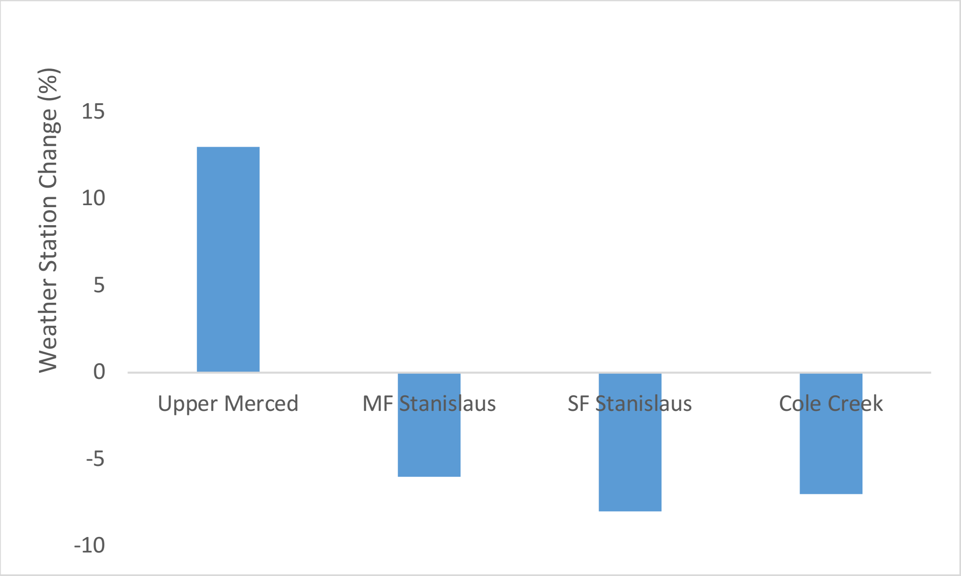

Figure 12. Percent Change in Median Pre-1973 and Post-1973 Annual Runoff Ratio, Using data from Remote Weather Stations (%)

Source：Boisramé et al., 2017

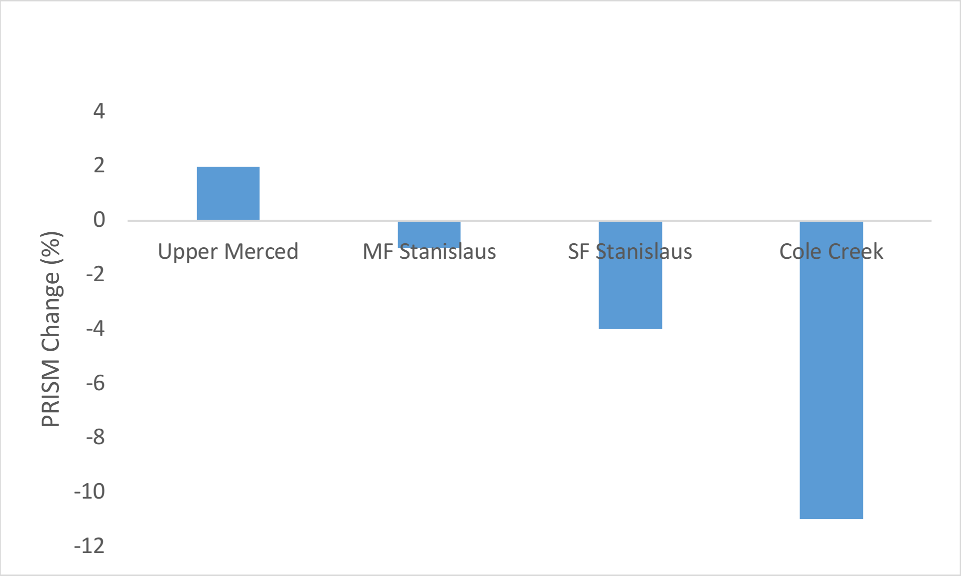

Figure 13. Percent Change in Median Pre-1973 and Post-1973 Annual Runoff Ratio, Using data from Parameter-elevation Regressions on Independent Slopes Model (%)

Source： Boisramé et al., 2017

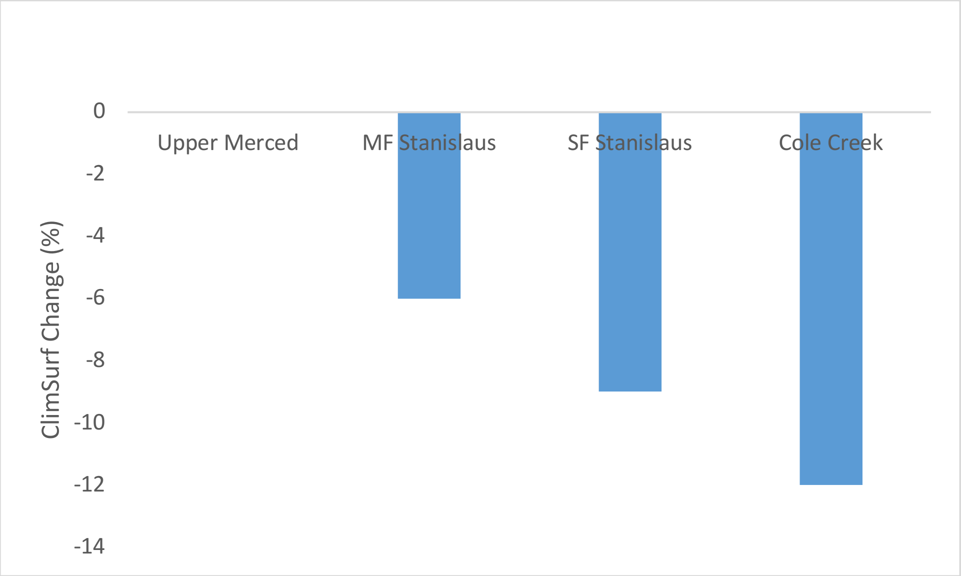

Figure 14. Percent Change in Median Pre-1973 and Post-1973 Annual Runoff Ratio, Using data from ClimSurf (%)

Source： Boisramé et al., 2017

The precipitation data of the unburned catchment of the four groups of sample sites were measured for many times by measuring weather station change, PRISM change and ClimSurf change, respectively. It can be seen that the change of runoff ratio before and after the fire in 1973 (figure12, figure13, figure14). Different from the three pairs, no matter under what frame of reference, the runoff ratio of Upper Merced is relatively stable and always in a positive trend, while the basic trend of runoff ratio of other watersheds is gradually decreasing.

4.2.2 Greater Khingan Mountains

The watersheds of the Emuer and Pangu are also similar. The sample lands of the burned and unburned parts of the Emuer river and Pangu river after the forest fire were selected for exploration and comparison (table 6).

Table 6. Watershed profile

			The area of burned level				
	Watershed area (km^2)	Burned area(km^2)	Mild	Medium	Serious	Serious fire proportion for the area of the fire	Serious fire proportion for the area of the fire
Emuer River	15523	7383	3092	2066	2225	30.1%	14.3%
Pangu River	3099	1902	643	431	828	43.5%	26.7%
Pangu River	1270	Unburned					

Source：Cai et al., 1995

The fire situation in the Emuer River Basin is relatively serious. The area burned accounted for 47.6% of the entire basin, of which the severely burned area reached more than 20,000 hectares. After the fire, this part of the area was treated as forest-free land, which drastically reduced the overall forest vegetation area and the river flow also changed accordingly. The actual measurement results (table7) show that the annual runoff after the fire is significantly higher than that before the fire when the annual precipitation before and after the fire is almost equal. However, the annual runoff in the year of the fire was obviously reduced. It is speculated that because of the huge heat brought to the watershed and the soil environment in the year of the fire, a large amount of water was evaporated.

Table 7. Changes in runoff before and after the Fire in the Emuer River Basin

	Year	Annual precipitation (mm)	Annual runoff (mm)	Annual runoff coefficient	The coverage of forestry(%)
Before fire	1986	416.1	133.2	0.32	78
After Fire	1987	370.2	96.3	0.26	63.7
	1988	345.3	148.3	0.43	63.7
	1989	434.1	169.3	0.39	63.7
	1990	523.7	204.2	0.39	63.7
Average	/	418.3	154.8	0.37	63.7

Source: Cai et al., 1995

Similar experimental data were also obtained in Pangu River City, which was severely burned. More than half of the area of Pangu River City was burned, and the fire was more serious. Among them, the severely burned area accounted for 43.5%, and the forest ecosystem was devastated. As a result, the forest coverage rate in the burned woodland watershed decreased from 68.7% to 42%, and the annual runoff in the watershed also changed significantly. Observation results show that (table8) compared with before the fire, the annual runoff of the river after the fire is lower than before the fire, but the annual runoff of the river shows a significant increase.

Table 8. Changes in flow before and after the fire in the Pangu River basin

	Year	Annual precipitation (mm)	Annual runoff (mm)	Annual runoff coefficient	The coverage of forestry(%)

Before fire	1985	431.1	179.2	0.42	68.7
After Fire	1988	370.4	205.1	0.55	42
	1989	410.2	208.3	0.51	42
	1990	474.6	214.6	0.45	42
	1991	454.1	240.7	0.53	42
	1992	459.5	226.8	0.49	42
Average	/	421.7	208	0.49	42

Source: Cai et al., 1995

The factor that has a more significant impact on runoff is mainly precipitation, and the state of vegetation will also have a certain impact. The relationship between precipitation and runoff was measured through the relationship between rainfall and runoff. Table 9 shows the rainfall-runoff model of the fired and unfired watersheds. It can be seen that the degree of correlation between runoff and precipitation was not closely related to before and after the fire. Vegetation in the watershed before or after the fire was relatively better. The correlation coefficient between rainfall and runoff in the fired plot is as high as 0.92, and the relationship between rainfall and runoff is very close, and the state of the forest is poor.

Table 9. Comparison of correlation between rainfall and runoff in unburned and burned basins.

	Rainfall-runoff relationship Q=f(p)	Coefficients	Relevance	The cover rate of forestry
Before fire	Q=-5.4+0.168p	0.63	Irrelevant	78%
After fire	Q=-19.34+0.226p	0.92	relevant	60.40%

Unburned	Q=8.63+0.001p	0.36	Irrelevant	81.50%

Source: Cai et al., 1995

4.3 Study on water quality after fire

4.3.1. The Experimental Lakes Area in northwestern Ontario

Figure 10 shows the changes in pH and hydrogen ion concentration in the watershed after a fire in the Northwestern Ontario Experimental Lakes. The PH value in the absence of fire from 1971 to 1980 was generally higher than the PH value after the fire in 1980. Correspondingly, the concentration of H ions in the watershed is generally higher after the fire than before the fire. Especially in 1982, the pH value was the lowest and the H + concentration was the highest. It can be concluded that the acidity of the watershed increased after the fire.

Table 10. Mean annual PH and mean annual hydrogen ion concentration in the stream at the Experimental Lakes Area before and after 1980's wildfire (1971-1989)

Year	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
pH	5.31	5.16	5.18	5.21	5.09	5.08	4.94	5.03	5.16	5.1	4.91	4.73	5.05	4.82	4.91	5.11	5.21	5.04	4.98
H^+	4.68	4.82	4.79	4.75	4.9	4.91	5.06	4.92	4.83	4.86	5.12	5.45	4.91	5.25	5.1	4.82	4.77	4.93	5.03

Source: Bayley et al., 1992

After the fire, the acidity of the watershed increased, and the concentration of H ions continued to increase, so the watershed was self-regulating. To maintain ion balance, an equal amount of cations are released. From 1980 to 1981, there was a significant relationship between Ca^{2+} Mg^{2+} and SO_4^{2-}concentrations in the watershed based on $Ca^{2+} + Mg^{2+} = SO_4^{2-} * 0.64 + 101.5$ ($R^2 = 0.83$).

4.3.2. The Blue Ridge Mountains of South Carolina

The water quality of the selected 5 sample streams was measured. Table 11 shows the watershed burned percent from low to high.

Table 11. Water quality monitoring site after the fire in National Sumter, South Carolina

Watershed	Burned Percent (%)	Comments
Crane Creek	0	Control watershed
Townes Creek	21.5	Includes Crane, Crossland and Wash Branch watersheds
Wash Branch	31.3	Burned only on north-facing slope from stream to ridgetop
Jumping Branch	66.4	Upper 2/3rds burned; primary ignition point of wildlife
Crossland Creek	100	Most severely burned; tornado crossed most of the watershed

Source：Neary and Currier, 1982

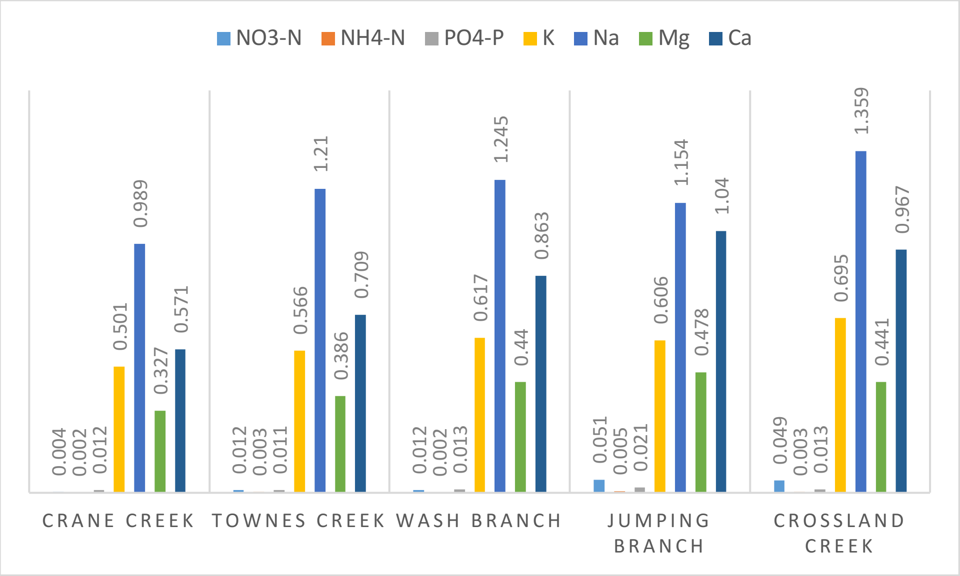

Figure 15. Mean nutrient and suspended solids concentrations in the stream

Source：Neary and Currier, 1982

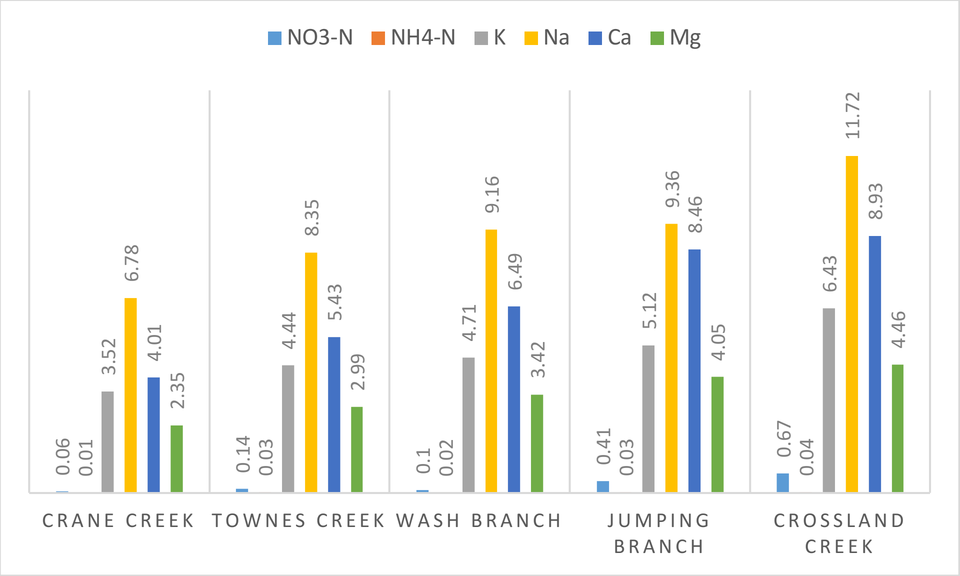

Figure 16. Outputs of ion in the stream for 1 year after the fire

Source：Neary and Currier, 1982

Figure 15 shows that although the content of NO_3-N is small, the increase is not high, but different content appears in the samples with different combustion levels. The content in Crane Creek is only 0.004 mg/l, but it is as high as 0.051 mg/l in the Jumping Branch area, which has been burned a lot. The content of NH_4-N is relatively less affected by combustion, and the value fluctuates between 0.002 mg/l and 0.005 mg/l. For PO_4-P, in addition to the content in Jumping Branch and its significantly as high as 0.021 mg/l, the content changes in other regions are also small, with values ranging from 0.011 mg/l to 0.013 mg/l.

Estimate and compare the annual production of NO_3-N, NH_4-N, K, Na, Ca, and Mg in five watersheds with different degrees of combustion (figure16). Obviously, the data of the CrosslandCreek sample watershed fluctuates greatly and is most affected by interference; the Crane Creek watershed has not been burned by fire, and its value fluctuations are small (Tiedemann et al., 1979)

5.0 DISCUSSION

5.1 Study on soil hydrological characteristics after fire

The Colorado experiment proves that wildfires can create thick layers of ash on the soil. The chart shows that this will affect soil water retention (Riley, 1979, 1989; Rawls et al., 2003). Further, changes in soil water content will respond differently to rainfall, thus altering runoff. Shortly after a wildfire occurs, the burned soil is drier than the unburned soil (figure 1, figure 2). As can be seen from the water content time series diagram, the unburned soil can respond to rainfall more quickly than the burned soil, which indicates that the permeability of the unburned soil is much higher than that of the burned soil. Especially after the two storms on October 12 and 22, the difference was extremely significant, indicating that the amount of rainwater in the unburned soil was higher than that in the burned soil (Ebel et al., 2012).

The soil moisture content measured by the thermogravimetric method showed similar results, while the burned soil (5 - 15 cm) showed spatial variability. The large change of water content in the soil after combustion may be related to the thickness of ash and the content of organic matter. The spatial variability of soil water content and matrix potential and these states may be necessary for the runoff generation process as it may affect the connectivity patterns of soil patches produced by runoff. It is well known that the generation of runoff depends on the initial conditions in the unburned soil (Zehe and Bloschl, 2004). The spatial variability of soil moisture content and matrix potential largely controls the amount of runoff, and it is well known that the generation of runoff depends on the initial conditions in the unburned soil (Zehe and Bloschl, 2004). As a result, the catchment area of the burned area is particularly sensitive to the initial hydrological conditions of dryness (Ebel et al., 2012).

Consistent with the above results, the experimental data of the Greater Khingan Mountains showed that forest fires caused significant decreases in waste layer thickness, soil moisture content and soil organic matter content (Neff et al., 2005; Dikici et al., 2006). It also leads to an increase in soil pH and a significant reduction in microbial biomass carbon. The decrease of soil moisture content leads to the rise of soil bulk density and the decrease of water-stable aggregates. The waste layer was burned out, which reduced the moisture content of the soil and caused high-indensity surface runoff (DeBano, 2000). At the same time, a large amount of fine clay particles are lost, leading to blockage of soil pores. In addition, the high temperature after fire changes the structure and quantity of soil minerals and organic matter, which eventually leads to an increase in soil bulk density (Certini, 2005).

5.2. Study on runoff after fire

Before the fire, the forest canopy closed, the wind speed decreased, the sun radiation weakened so that the forest evaporation weak. Water evaporation is mainly physiological transpiration and canopy interception loss of forest trees absorbing subsoil water (Daniel and Kulik, 1998). In the early stage after burning, the transpiration of trees disappeared, and the part of water trapped by the forest canopy directly entered the soil and flowed into the channel, increasing the river flow. Although the evaporation of forest land is also increased, it still cannot offset the increase of runoff, resulting in the annual runoff of the river is greater than before the fire (Cai et al., 1995). In the young stage of trees, their roots mainly absorb water from the upper layer of the soil for transpiration, resulting in the loss of runoff. At this stage, trees were fully closed and canopy interception loss was gradually restored and close to the state before fire. Therefore, the runoff loss was much greater than that before fire and the yield flow was less than that before fire. This trend of reduced runoff should continue until tree roots reach the subsoil (Cai et al., 1995).

The roots of trees gradually reach into the subsoil and begin to transport water upward from the underground runoff. More and more evaporation comes from the deep layer, and the upper layer supply gradually decreases, which makes the runoff continuously increase and gradually return to the original state before burning (Cai et al., 1995).

The plot data in Nevada (Boisrame et al., 2017) and the Greater Khingan Mountains (Cai et al., 1995) both reflect the above-mentioned view that after forest fires, the annual runoff will increase in most cases (table5, table7, table8, figure12, figure13, figure14). Although the increase in runoff is caused by forest fires, the increase in runoff is also related to the characteristics of precipitation, the area, intensity of fires, and the characteristics of watersheds (Neary et al., 2003). For the same watershed, the factors that have a large impact on runoff and are easy to change are mainly precipitation and vegetation conditions (Cai et al., 1995). The better the vegetation conditions, the more stable the runoff changes. There is a certain correlation between precipitation and runoff. With the increase of precipitation, the runoff shows a certain increase. The correlation is mainly restricted by other factors such as vegetation (Cai et al., 1995).

Table 5 shows that changes in the composition and organization of the ICB vegetation have also changed the way of burning and its impact. The frequency of ICB fires is relatively high, but the fire intensity is low, which are mainly low intensity and moderate intensity (Collins and Stephens, 2010). It can be seen from Table 9 that the correlation between runoff and rainfall was not closely related to the pre-fire and no-fire watersheds. This shows that runoff is not only dependent on rainfall but also affected by other factors such as vegetation in the watershed. In the watershed before or after the fire, the vegetation is in good condition, other factors are stable, and the interannual variation of runoff is stable, thereby reducing the impact of rainfall on runoff and reducing the correlation between the two (Cai et al., 1995). The situation after the fire was completely different. As the forest was burned, the forest community lost its redistribution of precipitation, and the waste layer with strong water storage capacity was burned in large quantities. It can be said that within a few years after the fire, the forest ecosystem is temporarily out of control for water, which makes runoff and rainfall dependent, and the relationship between the two is closer. The correlation coefficient between rainfall and runoff after burning is 0.92, which is much larger than that before and after burning (Cai et al., 1995).

5.3. Study on water quality after fire

Forest watersheds provide better water quality than agricultural and urban land. The chemical characteristics of water quality include some chemical constituents of water, such as N, P, K, Ca, and Mg. Watershed pH and H ion concentration are also important factors in determining water quality in the watershed. In a watershed system, the chemical composition or nutrients in the water (N, P, K, Ca, Mg, etc.) depend on weathering of rocks, decomposition of organic matter, and climatic characteristics (Wei and Sun, 2009). Nutrients in the watershed are cyclic. This cycle depends on the characteristics of the watershed itself (geological composition, size and shape of the watershed, etc.), and is also related to climate and vegetation (Wei and Sun, 2009). Warm and humid ecosystems have a faster nutrient cycle than arid and cold ecosystems. Vegetation absorbs and retains a large amount of nutrients, and then releases nutrients back to the ecosystem through return and decomposition of microorganisms (Wei and Sun, 2009). Forest fires change the nutrient cycle in the watershed system through the following aspects, thereby affecting the chemical composition of the water. 1 The fire has strengthened the mineralization of a large amount of organic matter, and many soluble nutrients have been released. 2 Due to the enhancement of soil and water loss, the released nutrients are more likely to enter the river system (Wei and Sun, 2009). Many released soluble nutrients cause significant leaching losses because they are not absorbed by the plant (Wei and Sun, 2009). The combined effect of these factors leads to an increase in the concentration of chemical constituents in the river after the fire (table 10, figure 15).

In a boreal forest catchment in the Experimental Lakes Area in northwestern Ontario, the acidity of the watershed increased after the fire, and the H ion concentration continued to increase, so the watershed was self-regulating (Bayley et al., 1992). Although some studies have confirmed that the concentration of some chemical components in water has increased significantly after forest fires (Wei and Sun, 2009), a large number of studies have shown that forest fires do not increase the concentration of chemical components in water, but increase the total amount, which is due to the increase caused by increased runoff (Wei and Sun, 2009). Although it is inconsistent with the above theory, it is generally believed that the impact of fire on water quality is short-lived. With the regeneration and restoration of vegetation, the above impact will soon disappear (Campbell et al., 1977). In the forest watersheds of South Carolina's Blue Ridge Mountains, monitoring and analysis of chemical composition concentrations in watersheds subjected to various degrees of fire (figure 16), the following conclusions were obtained: Ca, Mg, K concentrations in the first few rainfall runoffs after fires (Neary and Currier, 1982). It increased slightly, but this increase quickly disappeared in the future rainfall-runoff; the concentration of Na was hardly affected by the fire; the total concentration of N (both organic and inorganic) increased during the initial rainfall runoff, but it quickly returned to the level before the fire in the subsequent rain runoffs. This view is consistent with Campbell et al.'s (1977) study of northern Arizona, USA.

6.0 CONSLUDION

Forest fires are one of the most important natural disturbances, especially in drier areas. Forest fires have great variability in intensity and frequency, and the impact of forest fires on the ecosystem process of the watershed is directly related to the intensity and frequency of forest fires. For a given fire, the greater the intensity, the greater the impact. After a forest fire, the system often takes a long time to recover. If the forest system is not fully recovered and is subject to new fire disturbances, the impact of fire accumulation is greater. Therefore, the impact of forest fire is not only directly related to the intensity of the fire, but also related to the interference characteristics of the previous fire and the recovery of the forest after the interference. A devastating forest fire kills all the herbs, shrubs, and trees on the ground. In this way, the entire physical, chemical, and biological environment of the forest changed dramatically after the fire. These changes occur both on forest land and in water systems (rivers, wetlands, or lakes) linked to land systems.

In particular, it is worth mentioning the physical and chemical changes that take place on the forest surface during forest fires. The organic layer represented by waste on the forestland is the most important physical and chemical exchange layer between the above-ground trees and the underground soil. Physically, this organic layer maintains soil temperature, which also prevents or slows erosion or precipitation splashes. Thus, this layer maintains a better structure and penetration of the soil system. Chemically, this layer is a very important nutrient repository, where nutrients occur through important microbial processes such as the decomposition and release of waste. After forest fires, this layer is often burned into a layer of ash carbon. In addition, due to the chemical action in the combustion process, a large amount of organic matters and long chains of sugars are accumulated on the surface of soil particles or their interstitium, so that the soil surface presents an impermeable layer. Due to the impermeability of the soil surface after fire, the hydrological process or soil erosion in the watershed system also changed significantly. Therefore, it can be seen that a series of changes from soil to runoff to water quality after forest fire combustion are closely related.

An important part of understanding the impact of fire on water resources is understanding the processes involved. Much information has been included here to describe the scope of these effects. Forest fires have burned forest canopies and surface waste layers, resulting in a decrease or disappearance of the redistribution of forest ecosystems. The destruction of the good physical structure of forest soil leads to the decrease of the permeability and water storage capacity of undergrowth soil, and then aggravates the soil erosion. When the fire destroyed the surface vegetation, the evapotranspiration loss of the watershed changed from interception evaporation and vegetation transpiration to soil transpiration. In the short term after the fire, the decrease of water loss in the flow area directly shows the increase of water yield in the watershed. With the recovery of vegetation, the transpiration of vegetation reduces water yield in the watershed, and then gradually returns to the relative equilibrium before the fire.

It is obvious that forest fire has a significant regulating effect on the watershed and will cause damage to the watershed resources in a period of time. With the further development of high techlology, the focus of long-term comprehensive study is trend of forest hydrology. The interaction between fire, forest vegetation and hydrological process was coupled to the hydrological model to promote the faster and better development of forest hydrological domain.

7.0 LITERATURE CITED

Yanchun Zhou. Study on the influence of forest fire on evapotranspiration and runoff in watershed[D]. Frontiers of Forestry in China,2013,2(2), 163-168.

Shuren Yao, Jianhua Du. Effects of fire interference on forest hydrology [J]. Forest fire prevention, 2002 (3): 23-26.

B.A. Ebel, J.A. Moody, D.A. Martin Hydrologic conditions controlling runoff generation immediately after wildfire[J]. Water Resources Research,2012,48, 10.1029/2011WR011470

Fernάndez I, Cabaneiro A, Carballas T. Organic matter changes immediately after a wildfire in an Atlantic forest soil and comparison with laboratory soil heating[J]. Soil Biology and Biochemistry, 1997, 29(1): 1-11.

Horton J S, Kraebel C J. Development of vegetation after fire in the chamise chaparral of southern California[J]. Ecology, 1955, 36(2): 244-262.

Mataix-Solera J, Cerda A, Arcenegui V, et al. Fire effects on soil aggregation: a review[J]. Earth-Science Reviews, 2011, 109(1-2): 44-60.

Gerrits, A. M. J.: The role of interception in the hydrological cycle, PhD thesis, Delft University of Technology, Delft, 2010

Kozolows, T T.Fire andecosystems[M]. New York. Academic Press. 1974. 542-544

Lichen Song, Pingping He, Xiaoyang Cui. Effects of heavy forest fire on soil habitat factors in Greater Khingan Mountains[J]. Journal of ecology, 2015, 34(7): 1809-1814.

Chandler, C., Cheney, P., Thomas, P., Trabaud, L., & Williams, D. Fire in forestry[M].New York: Wiley & Sons, 1983,01,1-3.

Li, H., Zhang, Y., Zhang, X., Li, X., & Ao, T. Estimation of regional transpiration and evaporation using Penman-Monteith equation. Engineering Journal of Wuhan University/ Wuhan Daxue Xuebao, 2011,44(4), 457-461.

Cornish P M, Vertessy R A. Forest age-induced changes in evapotranspiration and water yield in a eucalypt forest[J]. Journal of Hydrology, 2001, 242(1-2): 43-63.

Tijiu Cai, Xiaofeng Zhou, Wenhua Yang. Effects of forest fire on river runoff in Greater Khingan Mountains. [D]. SCIENTIA SILVAE SINICAE,1995,05.

Versini P A, Velasco M, Cabello A, et al. Hydrological impact of forest fires and climate change in a Mediterranean basin[J]. Natural hazards, 2013, 66(2): 609-628.

Boisramé G, Thompson S, Collins B, et al. Managed wildfire effects on forest resilience and water in the Sierra Nevada[J]. Ecosystems, 2017, 20(4): 717-732.

Bosch J M, Hewlett J D. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration[J]. Journal of hydrology, 1982, 55(1-4): 3-23.

Neary D G, Ryan K C, DeBano L F. Wildland fire in ecosystems: effects of fire on soils and water[J]. Gen. Tech. Rep. RMRS-GTR-42-vol. 4. Ogden, UT: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 250 p., 2005, 42.

DeBano L F, Neary D G, Ffolliott P F. Fire effects on ecosystems[M]. John Wiley & Sons, New York. 1998.

Neary D G, Gottfried G J, Folliott P F. Post-wildfire watershed flood responses[C]//Proceedings of the 2nd International Fire Ecology Conference, Orlando, Florida. 2003: 16-20.

Gottfried, G. J., Neary, D. G., Baker Jr, M. B., & Ffolliott, P. F. Impacts of wildfires on hydrologic processes in forest ecosystems: two case studies[C]//Proceedings, First Interagency Conference on Research in the Watersheds. 2003: 27-30.

Gresswell R E. Fire and aquatic ecosystems in forested biomes of North America[J]. Transactions of the American fisheries society, 1999, 128(2): 193-221.

Emelko M B, Silins U, Bladon K D, et al. Implications of land disturbance on drinking water treatability in a changing climate: Demonstrating the need for "source water supply and protection" strategies[J]. Water research, 2011, 45(2): 461-472.

Bayley S E, Schindler D W, Parker B R, et al. Effects of forest fire and drought on acidity of a base-poor boreal forest stream: similarities between climatic warming and acidic precipitation[J]. Biogeochemistry, 1992, 17(3): 191-204.

Grren A. M. Fire and Australia Biota, CSIRO, 1981.172-185

Neary D G, Currier J B. Impact of wildfire and watershed restoration on water quality in South Carolina's Blue Ridge Mountains[J]. Southern Journal of Applied Forestry, 1982, 6(2): 81-90.

Topp G C, Ferré P A, Dane J H. Water content[J]. Methods of soil analysis. Part, 2002, 4: 417-545.

Koorevaar P, Menelik G, Dirksen C. Elements of soil physics[M]. Elsevier, (North-Holland), Amsterdam, The Netherlands.1983.

RColorBrewer, Suggests, and Maintainer Andy Liaw. "Package ‘randomForest’." University of California, Berkeley: Berkeley, CA, USA. 2018.

Liaw A, Wiener M, Breiman L, et al. Package “randomforest”[J].Machine Learning,2005(1):1-5.

Stainton M P, Capel M J, Armstrong F A. The chemical analysis of fresh water[R]. Can. Fish. Mar. Serv. Misc. Spec. 1977(25):166.

Tiedemann AR, Conrad CE, Dietrich JH, Hornbeck JW, Megahan WF, Viereck LA, Wade DD. Effects of fire on water: a state-of-knowledge review. General Technical Report WO-10, Forest Service, US Department of Agriculture; 1979(28).

Rawls J F, Johnson S L. Temporal and molecular separation of the kit receptor tyrosine kinase's roles in zebrafish melanocyte migration and survival[J]. Developmental biology, 2003, 262(1): 152-161.

Zehe E, Blöschl G. Predictability of hydrologic response at the plot and catchment scales: Role of initial conditions[J]. Water Resources Research, 2004, 40(10), W10202.

Dikici H, Yilmaz C H. Peat fire effects on some properties of an artificially drained peatland[J]. Journal of environmental quality, 2006, 35(3): 866-870.

DeBano L F. The role of fire and soil heating on water repellency in wildland environments: a review[J]. Journal of hydrology, 2000, 231: 195-206.

Certini G. Effects of fire on properties of forest soils: a review[J]. Oecologia, 2005, 143(1): 1-10.

T.M. Daniel, V. Kulik. Shrubbery forest fire hydrology. Journal of Heilongjiang University of Technology, 1998, (4). 63-66

Collins B. M, Stephens S L. Stand-replacing patches within a ‘mixed severity’fire regime: quantitative characterization using recent fires in a long-established natural fire area[J]. Landscape Ecology, 2010, 25(6): 927-939.

Campbell S, Thoms A. Ultrasound measurement of the fetal head to abdomen circumference ratio in the assessment of growth retardation[J]. BJOG: An International Journal of Obstetrics & Gynaecology, 1977, 84(3): 165-174.

Wei Xiaohua, Sun Ge. Basin Ecosystem Process and Management. Higher Education Press. 2009(12): 204-206; (13): 212-213.

Campbell, R.E., Baker, Jr., M. B., Ffolliott, P.F., Larson, F.R., Avery, C.C. Wildfire effects on a ponderosa pine ecosystem: an Arizona case study. Res. Pap. RM-191. Fort Collins, CO: U. S. Department of Agriculture, Forest service, Rocky Mountain Forest and Range Experiment Station. 1977(12).

Yanchun Zhou, Shiguo Xu, Yongqiang Zhang. Research progress on the influence of forest fire on watershed water cycle [J]. Inner Mongolia Forestry Investigation and Design, 2012(3):16.

Yanchun Zhou, Yongqiang Zhang, Shiguo Xu. Simulation of the effect of forest fire on runoff in typical small watershed [J]. Advances in water science, 2013, 24(2): 190-196.

Shuren Yao. Effects of fire disturbance on forest hydrology [J]. Journal of Forestry Research, 2003 (4): 12.

Liu, Z. M., Chen, H. S., & Liu, X. M. Characteristics and challenges in the study o the relationship between vegetation and disturbance[J]. Advances in Earth Science,2002, 17(4), 582-587.

Ice G G, Neary D. G, Adams P W. Effects of wildfire on soils and watershed processes[J]. Journal of Forestry, 2004, 102(6): 16-20.

Cornish P.M, Vertessy R A. Forest age-induced changes in evapotranspiration and water yield in a eucalypt forest[J]. Journal of Hydrology, 2001, 242(1-2): 43-63.

Gottfried G J, Neary D. G, Baker Jr M B, et al. Impacts of wildfires on hydrologic processes in forest ecosystems: two case studies[C]//Proceedings, First Interagency Conference on Research in the Watersheds. 2003: 27-30.