

EFFECT OF FIRE ON MINERALIZATION OF SOIL ORGANIC MATTER

Thesis

by

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(F-2017-46-M)**

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CERTIFICATE-I

This is to certify that the thesis titled, **“Effect of fire on mineralization of soil organic matter”** submitted in partial fulfillment of the requirements for the award of degree of **MASTER OF SCIENCE (AGRICULTURE)** in the discipline of **SOIL SCIENCE** to Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.) – 173 230 is a bonafide research work carried out by **Ms. Sakshi Vishvamitera (F-2017-46-M)** daughter of Shri Yashpal Sharma under my supervision and that no part of this thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of investigations have been fully acknowledged.

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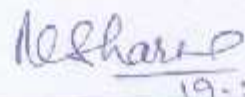
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This is to certify that the thesis titled "Effect of fire on mineralization of soil organic matter" submitted by Ms. Sakshi Vishvamitera (F-2017-46-M) daughter of Shri Yashpal Sharma to Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (HP) - 173 230 in partial fulfillment of the requirements for the award of degree of **MASTER OF SCIENCE (AGRICULTURE)** in the discipline of **SOIL SCIENCE** has been approved by the Student's Advisory Committee after an oral examination of the student in collaboration with the external examiner.



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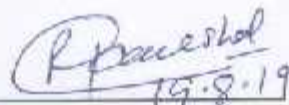


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I solely claim the responsibility of all errors and omissions.

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LIST OF ABBREVIATIONS

%	: Per cent
@	: At the rate
ANOVA	: Analysis of variance
CD	: Critical difference
cm	: Centimetre
dS m ⁻¹	: Deci Siemens per meter
EC	: Electrical conductivity
<i>et al.</i>	: <i>et</i> (“and”) <i>alii</i> (“ others”)
g	: gram
ha	: Hectare
i.e.	: That is
kg	: kilogram
kg ha ⁻¹	: kilogram per hectare
N	: Nitrogen
P	: Phosphorus
K	: Potassium
NS	: Non significant
°C	: Degree Celsius
OC	: Organic carbon
pH	: <i>Puissance de Hydrogen</i>
ppm	: Parts per million
RBD	: Randomized block design
mg kg ⁻¹	: Milligram per kilogram
Mg m ⁻³	: Megagram per cubic metre
µg g ⁻¹	: Microgram per gram
HP	: Himachal Pradesh
Pg	: Petagram (10 ¹⁵ g)
Tg	: Teragram (10 ¹² g)

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Chapter - 1

INTRODUCTION

Forests fires are the most common hazard and are as old as the forests themselves. They pose a threat not only to the forest wealth but also to the entire regime of the fauna and flora by seriously disturbing the bio-diversity, ecology and environment of a region. During summers, when there is no rain for months, the forests become littered with dry senescent leaves and twigs, which could burst into flames, ignited even by the slightest spark. The youngest mountain ranges of the Himalayas are the most vulnerable stretches of the world which are susceptible to forest fires. The Himachal and Uttarakhand Himalayas have been burning regularly during the last few summers, with colossal loss of vegetation cover. The forests of the Western Himalayas are more vulnerable to forest fires as compared to the forests in the Eastern Himalayas. This is due to the reason that forests of Eastern Himalayas grow in a high rainfall area. With large scale expansion of chir (Pine) forests in many areas of the Himalayas, the frequency and intensity of forest fires has also increased. The pine tree vegetation lies between 1,200 and 1,800 m above mean sea level, with mean annual rainfall of 600 mm and mean annual temperature of 16°C (Climent *et al.*, 2004).

The effects of fire on forest landscape are dependent on the duration of fire (Shakesby and Doerr, 2006). As a result of fire, changes like loss of vegetation due to high burn intensity, increased risk of erosion, soil hydrophobicity, loss of organic material and change in wildlife habitat can be instantly observed. However, with the passage of time after forest fire, vegetation will likely return, soils will stabilize and the ecology of the flora and fauna will progress towards pre-burn conditions. Fire acts as a vigorous mineralizing agent, causing the rapid transformation of organic nitrogen to inorganic forms which can be easily available to plants and microflora. Some people are of the view that fires consume nitrogen of the plants and surface soil layer, resulting in reduction of N pool in a burnt forest (Hyodo *et al.*, 2013). Wildfire is an integral component of forest ecosystems. Intermittent burns are natural disturbances that occur at varying intervals and severities, creating mosaics of even-aged stands and altering many components of the environment. Fire disturbance controls plant community succession and competition, native species genetics and eco-physiology, soil nutrient transformations and erosion; and pest behaviour (Brown and Smith, 2000). Fire regimes are the combination of fire factors (frequency, severity, spatial pattern and vegetation

type) that dominates in an area. They categorized forest fire regimes into four types: understory fires (short return-interval), stand replacing fires (crown fires), mixed severity fires (long return-interval crown fires), and non-fire regimes (no natural fires). They described that fire severity is determined from charring depth and remaining vegetation, both of which contribute to re-vegetation. Fire severity is a qualitative description of immediate fire effects on vegetation and soil litter. High severity fires can be lethal to many trees within the entire stand, and tend to effectively influence forest structure (Sherriff and Veblen, 2006).

Forest fires usually decrease the total nutrient pool (the total amount of nutrients present) on a site through some combination of oxidation, volatilization, ash transport, leaching, and erosion. For example, volatilization and oxidation in a low intensity slash fire reduced fuel nutrient pools in understory and forest floor by 54-75 per cent in nitrogen (N), 37-50 per cent in phosphorus (P), 43-66 per cent in potassium (K), 31-34 per cent in calcium (Ca), 25-49 per cent in magnesium (Mg), 25-43 per cent in manganese (Mn), and 35-54 per cent in boron (B). Though fire can diminish nutrient pool sizes, but it increases the nutrient availability. The immediate effect of fire on soil macronutrients is their loss through volatilization, because of high temperature. Nitrogen volatilization during prescribed fire is the dominant mechanism of nitrogen loss from these systems. At 500°C, half of the nitrogen in organic matter can be volatilized. It has been assumed that burning can increase the nitrogen concentration of the residual material (Raison *et al.*, 1986). Fire may affect soil nutrient status by direct addition of nutrients and by indirectly altering the soil environment. The nutrient enhancement is largely restricted to the surface soil (0-5 cm) while, only soluble N appeared to increase in the subsurface soil (5-10 cm). The most significant short-term effects of the wildfire are the increases in the soil solution concentrations and/or leaching of mineral forms of N, S and P.

Some nutrient dynamics are more sensitive to fires than others. The concentration of potassium, calcium, and magnesium ions in the soil can increase or be unaffected by fires, whereas, nitrogen and sulphur concentration often decreases (Hough, 1981). Fire intensity is usually the most critical factor affecting post-fire nutrient dynamics, with greater nutrient losses occurring with higher fire intensity. Fire intensity both directly and indirectly affect nutrient pools and cycling. Fire temperature directly determines the amounts and kinds of nutrients that will be volatilized. For instance, N begins volatilizing out of organic matter at only 200° C, whereas, Ca must be heated to 1240° C for vaporization to occur (Neary *et al.*,

1999). High intensity fires can also change the physical characteristics of the soil making it more susceptible to nutrient loss through erosion (McColl and Grigal, 1977).

Wildfires in pine forests result in an increase in the net N mineralization by removal of the portion of the forest floor, volatilization of terpenoids, denaturation of organic N compounds and killing of soil microbial biomass. Wan *et al.* (2001) found that nutrient mobilisation during intense fires decreases long-term nutrient availability in soil which may inhibit microbial growth. Several studies revealed that ash residues deposited during wildfire can reduce N losses by increasing soil N retention and enhancing plant N acquisition (Grogan *et al.*, 2000b).

Forest productivity and N-turnover rates may be closely related and have been suggested as strong controls, both together and individually, on nitrification and net mineralization in forest soils. Examination of the above ground cycle of nitrogen in forests suggests that such relationships 'ought to exist', and several studies have sought indices of N-availability which correlate with productivity.

Fires are often major features of forest disruption and renovation. Widely investigated is their role in altering floristic composition (Cammeraat and Imeson, 1999), promoting tree regeneration (Martínez-Sánchez *et al.*, 1999), enhancing timber production (Vihnanek and Ballard, 1988), and conditioning human ecology (Caldararo, 2002).

The global carbon and nitrogen emissions from fires have been estimated to be 3.53 Pg/year (Werf *et al.*, 2004) and 8 Tg N/year (Crutzen and Lelieveld, 2001), respectively. There are five principal global C pools. The oceanic pool is the largest, followed by the geologic, pedologic (soil), biotic and the atmospheric pool. Soil organic matter (SOM) represents the third largest terrestrial carbon pool, with a global estimated total of 1526 Pg C (Lal, 2004). The organic horizon is critical component of ecosystem sustainability in that it provides a protective soil cover that mitigates erosion, aids in regulating soil temperature, provides habitat and substrates for soil biota and can be major source of readily mineralizable nutrients. The most intuitive change soil experience during burning is loss of organic matter. The effect of fire on SOM is highly variable from total destruction of SOM to partially scorching, depending on fire severity, dryness of the surface OM and fire type. Low-intensity prescribed fire usually results in little change in soil carbon, but intense fire or wildfire can result in a huge loss of soil carbon. Fernandez *et al.* (1997) suggested that in low intensity

fire, lipids are least affected group, whereas, 90 per cent of water soluble cellulose, hemicelluloses and lignin are being destroyed.

Fire severity consists of two components: intensity and duration. Intensity is the rate at which a fire produces thermal energy. Although heat in moist soil is transported faster and penetrates deeper, latent heat of vaporisation prevents soil temperature from exceeding 95 °C until water completely vaporises (Campbell *et al.*, 1994), the temperature then typically rises to 200–300 °C (Franklin *et al.*, 1997). The combination of combustion and heat transfer produces steep temperature gradients in soil. Temperatures at 5 cm in the mineral soil rarely exceed 150 °C and often no heating occurs below 20–30 cm (DeBano, 2000). Duration is perhaps the component of fire severity that results in the greatest belowground damage. In fact, intense but fast moving fires do not transfer much heat down to more than few centimetres below the surface. After fires, soil temperatures can remain high for a period from a few minutes to several days. Basically, there are two types of forest fires: prescribed (controlled) fires and wildfires. Prescribed burning of naturally accumulated forest floor or slash following tree harvest is a standard practice to reduce fuel levels, with the intention of minimising the extent and severity of wildfires or facilitating germination and growth of desired forest species. They are primed when soil is moderately moist, and consequently they show a low severity (Walstad *et al.*, 1990). In contrast, wildfires generally occur in the presence of an abundant and dry fuel load and, thus, are very severe.

Fire is one of the major elements of global climate change which influences the soil microbial communities and ultimately their role to the carbon dynamics of terrestrial ecosystem. Fire is reported to reduce microbial abundance by about 33.2 per cent (Dooley and Treseder, 2012). It has been observed that burning favours bacteria over fungi (Sharma, 1981; Deka and Mishra, 1983) meaning that the fungal population is more affected by forest fires. Fire influences a variety of soil physical and chemical properties including loss of soil structure, reduction of organic matter, porosity and increased pH (Certini, 2005).

Wildfire behaves differently in different ecosystems, the effects of which must be evaluated accordingly. A plethora of recent works has investigated what type of modification selected properties of forest soils undergo following fire. Keeping in view the diverse effects of forest fires and the importance of some soil properties in maintaining ecological balance, as well as the role of nitrogen and carbon in ecosystem, the present studies entitled **“Effect of**

fire on mineralization of soil organic matter” were carried out with the following objectives:

- i) To determine the effects of forest fires on net Nitrogen mineralization and carbon
- ii) To evaluate the effects of forest fires on the microbial biomass and their activity

Chapter - 2

REVIEW OF LITERATURE

Fire is recognised as a potent risk factor in woody and bushy environments. Fire is a good servant but a bad master. In the mid- Himalayan region, the fire season starts in March/April and continues up to June, when the pre- monsoons arrive. Wildfires destroy not only flora (tree, herbs, grasslands etc.) and their diversity, but also considerable long term negative impacts are seen on the fauna, including wild endangered species. Fire can also have a marked influence on the physico-chemical and biological properties of soil including texture, colour, bulk density, pH, porosity, organic matter, nutrient availability and soil biota. The work done on different aspects in India and abroad related to the **“Effect of fire on mineralization of soil organic matter”** is reviewed under the following headings:

- 2.1 Effect of fire on soil carbon
- 2.2 Effect of fire on net N mineralization
- 2.3 Effect of fire on microbial biomass carbon
- 2.4 Effect of fire on physico-chemical and biological properties
- 2.5 Comparative effects of fires on soil properties under different land uses

2.1 EFFECT OF FIRE ON SOIL CARBON

Naveh (1960) reported that in the first year after burning of dense sclerophyll shrubland there was a loss in organic matter of about 20 per cent in the upper 4 cm of the soil. At the same time there was a significant increase in Ca^{2+} and K^+ content and a striking stimulation of grass production in the brush ashes. In another studies, on the changes in soil organic matter and nitrogen fertility during the slash and burn and cropping phases in experimental shifting cultivation (Kumada *et al.*, 1985), soils were sampled at six periods, I (before forest clearing), II (immediately before burning), III (immediately after burning), IV, V and VI (10, 20 and 30 months after burning). They concluded that the amounts of humic and fulvic acids increased from periods I to II and decreased afterwards.

Rashid (1987) studied the effects of wildfire on the dynamics of pH, organic C, total and mineral N and *in-vitro* C and N mineralization in the soil under oak trees. Soil samples were taken 5 to 21 months after the fire. There were sharp rises in the concentration of

organic C, total and mineral N in addition to *in-vitro* mineralization activities in the burned surface soil collected 5 months after the fire and these dropped off in the subsequent samples approaching or falling below the values obtained in the unburned surface soil after 21 months. Moreover, at a depth of 5–15 cm only slight or no increases over unburned soil were observed.

The most intuitive change soils experience during burning is the loss of organic matter. Depending on fire severity, the impact on organic matter consists of slight distillation (volatilisation of minor constituents), charring or complete oxidation. Substantial consumption of organic matter begins in the 200–250°C range, to complete at around 460°C (Giovannini *et al.*, 1988). Combustion causes reduction or total removal of the forest floor. The recovery of soil organic matter in the burnt areas starts with the natural or artificial reintroduction of vegetation and generally is fast, due to the high net primary productivity of secondary ecological successions.

Almendros *et al.* (1992) found that humic acids and fulvic acids subjected to heating at 350°C for 120 seconds experienced decarboxylation and increase of aromatic carbons. Elimination of alkyl structures occurs preferentially after additional heating, when no further aromatic neo-formation is observed. Wildfires dramatically reduced the amount and quality of soil organic carbon (Gillon *et al.*, 1995), leaving the most recalcitrant organic fraction in the soil. This lower organic matter quality may explain the decrease in net mineralization rates in the burned plots. Ferná'ndez *et al.* (1997) collected samples from the top 10 cm of soil immediately after a high-intensity wildfire in *Pinus sylvestris* forest to determine the change in quantity, chemical composition and mineralization kinetics of the organic matter. Their study revealed that the lowest temperature was totally ineffective, the highest one led to complete oxidation of soil organic matter and the intermediate temperatures imposed major structural changes. At 220°C, where 37 per cent of organic matter was lost, all main C forms were pyrolysed although at different rates: 70–80 per cent for cellulose + hemicellulose, about 50 per cent for both lignin and water-soluble compounds and 10–25 per cent for lipids. Moreover, the humic fraction was reduced by heating, but less than the non-humic fraction.

Slaughter *et al.* (1998) studied the changes in carbon content after fire and reported that combustion losses were 19 per cent of pre-fire above ground carbon mass and an additional 4 per cent of carbon mass lost in the following 3–4 years. Ferná'ndez *et al.* (1999)

in another study, explained that long-term fire in the *Pinus pinaster* forest increased the soil organic carbon and declined the mineralisation rate and further suggested that the effects of fire on soil organic C must be evaluated not only on a quantitative basis but also on a qualitative basis. In a study from 48 sites, on the long term effects of forest fires, Johnson and Curtis (2001) observed a positive effect of forest fires on the content of soil organic carbon, which demonstrated the ability of fires to enhance soil C sequestration significantly.

Wirth *et al.* (2002) studied the effect of fire and site type on carbon and nitrogen balances by following the change of total and component C and N pools along four chronosequences of fire-prone Siberian Scots pine ecosystems, which differed in the mean return interval of surface fires (unburned-moderately burned, 40 years-heavily burned, 25 years) and site quality (lichen versus *Vaccinium* site type). On the *Vaccinium* site type (higher site quality) the organic layer C pool oscillated in response to recurring surface fires and its C pool was dependent on time after fire increasing at a rate of about 1.5 mol C m^{-2} year during the first 40 years and then reaching a plateau of 170 mol C m^{-2} . The total ecosystem N pool was $7.4 \pm 1.5 \text{ mol N m}^{-2}$, out of which only 25 per cent were stored in biomass or coarse woody debris. Gonz lez-Pe rez *et al.* (2004) studied the effects of fire on soil organic matter and their study revealed that the fire removed the external oxygen groups that yields materials with comparatively reduced solubility, reduction of the chain length of alkyl compounds such as alkanes, fatty acids and alcohols, aromatisation of sugars and lipids occur, formation of heterocyclic N compounds, macromolecular condensation of humic substances and production of an almost unalterable component, the so called black carbon.

2.2 EFFECT OF FIRE ON NET N MINERALIZATION

Raison (1979) studied the effect of fire on soil N availability, ash deposition of N previously contained in vegetation, alteration of soil microclimate by removal of vegetation/litter, and changes in microbial N mineralization resulting from changes in soil C stocks. They reported that soil heating causes an increase in $\text{NH}_4\text{-N}$ concentrations in the short term and may lead to accelerated mineralization of the remnant, pyromorphic soil organic matter in the long term. Moreover, strong heating increased $\text{NH}_4^+\text{-N}$ levels from a few to more than 400 ppm in some soils but nitrates are decomposed above 150°C . Hobbs and Schimel (1984) reported that fire caused increased rates of N mineralization for one year in a mountain grassland, and for 2 years in a mountain shrub community. The rapid recovery

of the vegetation in the grassland caused rapid convergence of burned to unburned conditions.

Vance and Henderson (1984) studied the surface soil of oak-hickory forest plots subjected to 30 years of annual and periodic (4-year) prescribed burning to determine the effect of the burning treatments on mineralizable N and concluded that burning significantly reduced the quantity of extractable NH_4^+ over all sampling dates. Also, the annual burning resulted in lower amounts than burning every four years. Burning also significantly reduced the quantity of N mineralized during incubation. Covington and Sackett (1986) conducted a study to determine the effects of different burning intervals on soil N status in substands of sapling, pole and saw timber-sized ponderosa pine, where sampled plots burned at 1, 2 and 4-year intervals by three strata at two depths (0-5 and 5-15 cm). Generally, NH_4^+ and NO_3^- concentrations were higher on plots repeatedly burned than on unburned controls. Moreover, plots not re-burned for 4 to 5 years had concentrations similar to controls. No significant difference in total (organically bound) N was found among treatments and thus they concluded that frequent periodic burning can be used to enhance N availability.

Stock and Lewis (1986) studied the role of fire as a mineralizing agent in a South African coastal fynbos ecosystem and reported an increase in total N (input of 66 kg N ha^{-1}) and exchangeable NH_4^+ -N concentrations at the soil surface immediately after a fire as direct effects, and the indirect effects of fire on soil N observed in the year following the fire were an increase in total N concentrations down the profile and increased concentrations of NO_3^- -N which lasted nine months. Moreover, the availability of NH_4^+ -N was for a short duration. Klopatek (1987) studied the effect of fire on the mineral soils in the interspaces and under canopy of three pinyon-juniper woodland communities to determine their nutrient status and potential N mineralization and nitrification and reported that recovery of soil nutrient levels was very slow and even 35 years after a wildfire, N and P concentrations had not recovered to levels found in a control stand not subjected to burning for the last 300 years.

In a study on the effects of burning at 2 and 4 year intervals over a 24 year period on N mineralisation and immobilisation in a loblolly pine stand, Bell and Binkley (1989) reported that net N mineralisation in 10 day laboratory incubation of mineral soil was greatest in the control (210 mg N/m^2), intermediate for the 2-year interval burn treatment (87 mg N/m^2) and lowest for the 4-year interval burn treatment (78 mg N/m^2). Moreover, forest floor and mineral soil C/N ratio were greatest for the burn treatments than for the control and both

burning regimes appeared to increase N immobilisation and decrease N availability on the site. Weston and Attiwill (1990) studied the effect of fire and forest harvesting on inorganic N, net N-mineralization and on the leaching of NO_3^- -N and metallic cations in soils of *Eucalyptus regnans* forests of South- Eastern Australia and found that in the topsoil of an *E. regnans* forest, fire-induced inorganic N increased to three times the original concentration over the first 205 days, however, after 485 days a return to the pre-fire level was observed. Moreover, the concentrations of NO_3^- -N and metallic cations in soil solution increased with increase in fire intensity.

Singh and Singh (1991) reported that annual N-mineralization was significantly higher in the burnt forest site followed by unburnt and control site. The higher rate of N-mineralization in the burnt site was ascribed to the larger input of decomposable substrate. Covington and Sackett (1992) studied the changes in soil mineral nitrogen following prescribed burning in ponderosa pine forest near Flagstaff, AZ, USA and reported that immediately after burning, ammonium-nitrogen (NH_4^+ -N) increased from 2.3 to 45.1 mg kg^{-1} in the old-growth sub stands, 1.3 to 26.7 mg kg^{-1} in the pole sub stands and 1.3 to 8.3 mg kg^{-1} in the sapling sub stands. These differences in NH_4^+ -N among the sub stand types are directly correlated with differences in the initial forest floor weight and the amount of forest floor burned. Nitrate-nitrogen (NO_3^- -N) was not changed immediately after burning. After one year of burning, NH_4^+ -N had declined substantially with only the old-growth sub stands being significantly higher than controls (30.0 versus 2.56 mg kg^{-1}). Much of this decline showed up as an increase in NO_3^- -N, particularly for the old-growth sub stands where NO_3^- -N was 18.6 mg kg^{-1} on burned plots compared with 0.03 mg kg^{-1} in control. These results support the conclusion that while increases in NH_4^+ -N are an immediate effect of burning (most likely from NH_4^+ -N produced by pyrolysis of forest floor material), nitrate increases, which occur later, are most likely caused by nitrification of the high NH_4^+ -N produced immediately after burning.

In a study on the effect of fire on nitrogen mineralization and nitrification in South-Eastern Australian forest soil, Bauhus *et al.* (1993) found that net N mineralization in ash bed soil was not significantly different from unburnt or phosphate fertilized soils (13.1, 14.7 and 17.8 mg N in kg^{-1} , respectively) but was lower than in limed soil (59.3 mg N min kg^{-1}). Prieto-Fernandez *et al.* (1993) studied the short-term effects of a wildfire on the nitrogen status and its mineralization kinetics in an Atlantic forest soil by comparing the surface (0-5

cm) and sub-surface (5-10 cm) layers from the burnt soil with the corresponding layers from the same unburnt soil. N mineralization kinetics were determined by aerobic incubation at 28°C for 11 weeks and they concluded that the fire increased the total N content in the surface layer but not in the sub-surface. Total inorganic N, which was mainly in the form of NH_4^+ -N increased after the burning in both the layers, whereas, NO_3^- -N content which was very low only increased in the sub-surface layer. The fire increased the N mineralization capacity but did not modify the organic N mineralization behaviour. Moreover, ammonification largely predominated over nitrification in both the unburnt and the burnt soils. The potentially mineralizable N decreased and the kinetic constant increased in the burnt samples showing that the wildfire reduced the mineralizable organic-N reserves and increased the mineralization rate, thus predicting a rapid depletion of the labile organic N.

Guinto *et al.* (1999) carried out an experiment on the effects of burning on *in-situ* extractable nitrogen (NH_4^+ -N+ NO_3^- -N) and net N mineralisation following scheduled fuel reduction burns in repeatedly burnt dry and wet sclerophyll forest sites in South-East Queensland and the results showed that at the dry sclerophyll site, extractable N and net N mineralisation for 1 year were largely unaffected by burning, while at the wet sclerophyll site, these parameters decreased. ^{13}C NMR analysis of soil samples from the wet sclerophyll site revealed that there was a significant reduction in the proportion of O-alkyl (alkoxy/carbohydrate) C with increasing burning frequency. Moreover, the ratio of alkyl C to O-alkyl C, a proposed index of organic matter decomposition increased with increasing burning frequency and high ratio of alkyl C to O-alkyl C, suggests low amounts of carbohydrates relative to waxes and cutins, which could, in turn, lead to slower mineralisation.

Castaldi and Aragosa (2002) investigated the main factors influencing the variability of nitrification and denitrification enzyme activity (DEA) in soils of a Mediterranean shrubland, in an undisturbed area and in plots treated with experimental fires of two different intensities. Soil was sampled four times during one year after burning, characterised by different environmental conditions. In the control, net nitrification ranged from 0.95 to 1.32 g NO_3^- -N g^{-1} day^{-1} and did not show significant average differences among sampling events, probably because water content and NH_4^+ -N availability were both limiting the process at any time. Overall, nitrification seemed associated with microsites where NH_4^+ -N production was higher. This pattern was not evident in the burned plots, where a partial reduction of activity

immediately after burning was observed. DEA showed higher variability among sampling events, as compared with nitrification, with a peak in winter. In the burned sites, water content, organic C and NO_3^- -N content concurred to explain DEA variability together with NH_4^+ -N availability and nitrification activity. Moreover, plots treated with intense fire showed the lowest values of DEA, especially in the period more favourable to this activity.

DeLuca *et al.* (2002) studied N mineralization rates, nitrification rates and sorption of free phenolic compounds along a fire-induced chronosequence of scot pine forest in Northern Sweden where replicate ionic resin capsules (used to assess net N mineralization and nitrification) and non-ionic carbonaceous resin capsules (used to assess free phenolic compounds) were installed at the interface of humus and mineral soil. A highly significant correlation was observed between site age and net sorption of inorganic N to resin capsules. Net accumulation of NH_4^+ and NO_3^- on resin capsules followed a linear decrease with time as a result of increased N immobilization with successional C loading. Moreover, NO_3^- sorption to resin capsules followed a logarithmic decrease that may be related to a logarithmic increase in dwarf shrub cover and decreased soil charcoal sorption potential along this chronosequence.

Nardoto and Bustamante (2003) studied the effects of fire on net N mineralization and soil microbial biomass in burned and unburned sites from April 1998-2000 and concluded that four months after fire (September 1998) there was a significant increase of inorganic-N due to an increase in NH_4^+ -N concentration measured at the 0 to 5 cm soil layer. However, in the following months after the fire, NH_4^+ -N concentration decreased in comparison to pre-fire levels. The NH_4^+ -N concentration ranged between 3 and 34 mg kg^{-1} in the burned site and between 3 and 22 mg kg^{-1} in the unburned site. The pH values were significantly higher in the burned site while the soil moisture content was significantly higher in the unburned site. The soil C/N ratio was 22/1 and the available NO_3^- -N ranged between 1.5 and 2.8 mg kg^{-1} . While studying the effects of experimental fire on soil microorganisms and soil emissions of carbon dioxide in Savannah woodland of the Gambella region in Ethiopia (Andersson *et al.*, 2004) reported that the fire led to destruction of the vegetation and combustion of allelopathic compounds, such as terpenes and phenolics, increased nitrifier abundance and thus the transformation of NH_4^+ to NO_3^- . The microbial biomass C was 52 per cent (fumigation–extraction) and 20 per cent (substrate-induced respiration) higher in burned than unburned plots 12 days after burning.

Knicker *et al.* (2005) conducted an experiment on effect of fire on transformation of C and N forms in different organic soil fractions from a Dystric Cambisol under a Mediterranean pine forest in Spain and concluded that five years after a fire, most of the soil heteroaromatic N was identified in the humin fraction, although minor amounts were detected in the humic and fulvic fractions. Moreover, pyrrole- type N forms were not detected in the solid state. Similarly, MacKenzie *et al.* (2006) studied the effect of fire on N cycling in low elevation forests of Western Montana and reported that in fire excluded forest sites, there was significant reduction in N mineralisation with resin sorbed NH_4^+ -N concentrations approaching zero asymptotically between 20 and 50 years since fire and NO_3^- -N concentrations approaching zero by sigmoidal curve with inflection point between 40 and 70 years after fire. Although, microbial biomass and respiration showed no significant change with time since fire. Moreover, increased metabolic quotient and decreased anthrone reactive carbon indicated reduced C availability and increased microbial stress with the passage of time after fire.

DeLuca *et al.* (2006) carried out a laboratory experiments on soils from ponderosa pine forests to determine the influence of charcoal which is a major by-product of forest fires on soil N dynamics and nitrification. The addition of NH_4^+ to forest soils had absolutely no effect on nitrification demonstrating that this process is not substrate limited. The amendment of these soils with NH_4^+ and field collected charcoal (1%w/w) significantly increased the nitrification potential, net nitrification, gross nitrification and decreased the solution concentrations of plant secondary compounds. The increase in gross nitrification in forest soils and lack of effect on grassland soils suggests that charcoal may alleviate factors that otherwise inhibit the activity of the nitrifying microbial community in forest soils.

Turner *et al.* (2007) studied inorganic nitrogen pools and mineralization rates after stand-replacing wildfires in the Greater Yellowstone Ecosystem, Wyoming. After fires that burned in summer 2000, soil ammonium concentration peaked in 2001 (33 mg NH_4^+ -N kg soil⁻¹), soil nitrate increased subsequently (2.7 mg NO_3^- -N kg soil⁻¹ in 2003) but was still low. However, annual net ammonification rates were largely negative from 2001 to 2004 indicating the ammonium depletion. Moreover, net nitrification rates remained positive and annual net nitrogen mineralization (net ammonification plus net nitrification) remained low.

Boerner *et al.* (2008) studied the initial effects of fire and mechanical thinning on N transformation and C:N ratio of soil organic matter and mineral soil in 8 North American forested ecosystems and concluded that across all 8 sites, there were no statistically significant effects of the three manipulative treatments (prescribed fire, mechanical thinning and their combination) on net N mineralisation or net nitrification, whereas soil C:N ratio increased modestly after mechanical thinning, but not after prescribed fire and the combination of fire and thinning. Moreover, there was a statistically significant reduction in forest floor C:N ratio as a result of all three treatments.

Duran *et al.* (2009) studied the effect of wildfire on net N mineralisation rates and soil N and P pool in *Pinus canariensis* forests in La Palma Island (Canary Islands) and reported that after few days of wildfire occurrence, burned pine forest stands had lower net mineralization rates (both nitrification and ammonification) as compared to unburned pine forest stands and these differences were higher for the winter sampling date than for the spring sampling date. Unlike extractable N and N mineralization rates, extractable P levels of burned plots exhibited a gradual recovery over time after an initial decrease.

Liao *et al.* (2013) studied the fire effects on the N cycle in both a high-phosphorus (P) restored wetland and a low-P reference calcareous wetland (marl prairie) in the Hole-in-the-Donut region of the Southern Everglades and observed that both restored and reference sites showed an increase in extractable $\text{NO}_3\text{-N}$ and $\text{NH}_4^+\text{-N}$ two days after the fire. The increase of extractable inorganic N was greater at the reference site (i.e., approximately twice that of the control plots) compared to the restored site (i.e., only 20 per cent to 40 per cent higher than the control plots). At longer time scales (one month to one year after the fire), the extractable $\text{NO}_3\text{-N}$ remained higher in the burn plots than in the control plots for the reference site, but the extractable $\text{NH}_4^+\text{-N}$ at both restored and reference sites dropped to levels below that of the control plot one month after the fire.

2.3 EFFECT OF FIRE ON MICROBIAL BIOMASS CARBON

Fritze *et al.* (1993) conducted a study on development of humus layer soil microbial biomass C (C_{mic}) and N (N_{mic}), fungal biomass (as soil ergosterol content), microbial respiration activity and the soil organic C (C_{org}) and N (N_{tot}) in coniferous forest soils that had received a single prescribed fire treatment at different times over a period of forty five years and the ratio of soil respiration rate to microbial biomass C ($q\text{CO}_2$) $C_{\text{mic}}/C_{\text{org}}$ and $N_{\text{mic}}/N_{\text{tot}}$

percentages were derived from the measurements taken and reported that the first twelve years were characterized by increasing C_{mic}/C_{org} and N_{mic}/N_{tot} percentages, which then stabilized at mean values of 1.3 and 5.5 per cent, respectively. The observed rise in the C_{mic} within a large pool of C_{org} suggested increasing availability of energy-rich C sources. These C sources are probably derived from the organic C input resulting from post-fire plant succession.

Baath *et al.* (1995) carried out a experiment in clear-cut, wood-ash fertilized and prescribed burned (both in standing and clear-cut) coniferous forests to study the effects of treatments on microbial biomass and community structure using humus phospholipid fatty acid (PLFA) analysis and concluded that the microbial biomass (total PLFAs) decreased significantly due to the highest rate of wood-ash fertilization, clear-cutting, and the two different fire treatments, when compared to control amounts. Moreover, fungi appeared more seriously reduced by these treatments than bacteria, as revealed by a decreased index of fungal: bacterial PLFAs when compared to the control.

Acea and Carballas (1996) study physiological groups of soil microorganisms in *Pinus pinaster* forest to assess their response to wildfire-induced soil changes. Microbial fluctuations were recorded one month and one year after the fire, both in the field and during controlled soil incubations. In both the burned and the unburned soil, starch-mineralizing microbes predominated over cellulose-mineralizing microbes. There were a relatively high number of ammonium-producers, whereas nitrite and nitrate producers were scarce. In the short term, burning produced a decreasing to nearly undetectable number in cellulase-producers ammonifying microbes increased and the nitrifying groups did not change. One year after the wildfire, the burning effect was slightly overcome by cellulolytic microorganisms and the amylolytic population was slightly decreased, improvement of ammonifiers was reduced, ammonium oxidizers were positively affected and nitrite oxidizers continued to be unaffected by the fire. The trends of populations during soil incubation indicated that in the long term, the effect of burning will probably be nil on ammonifiers, somewhat negative on cellulolytic and amylolytic microbes and slightly positive on nitrite and nitrate formers.

Acea and Carballas (1999) in another study on the effect of soil heating and organic amendment on microbial fluctuation in soil not inoculated (H) or inoculated with 0.5 per cent

of fresh soil (Hi) and amended with wheat straw (Hi+WS) or poultry manure (Hi+PM) and reported that saprophytic bacteria predominated over the other microbial groups, followed by fungal propagules and actinomycetes, found that the fungal mycelium was relatively well developed, whereas the numbers of photoautotrophs, cyanobacteria and algae were low. With regard to the N-mineralizers, there was a relatively high number of ammonifiers, while chemoautotrophic nitrifiers both NH_4^+ and NO_3^- oxidizers were scarce. Moreover, organic amendment (WS or PM) neither inhibited microbial proliferation nor changed the order of the sizes of the various subgroups.

Ajwa *et al.* (1999) studied microbial biomass C (MBC), microbial biomass N (MBN) and eight enzyme activities involved in the cycling of C, N, P and S in the surface soil (0 ± 5 cm) of an Irwin silty clay loam soil in a tallgrass prairie ecosystem and reported that long-term burning and N fertilization of the tallgrass prairie soil reduced microbial biomass C and microbial biomass N relative to the unburned-unfertilized treatment. Moreover, long-term burning significantly increased the activities of urease and acid phosphatase but decreased activities of β -glucosidase, deaminase and alkaline phosphatase and long-term N fertilization significantly increased the activities of β -glucosidase and acid phosphatase but decreased urease activity.

DeBano (1990) studied effects of fire on nutrient cycling, physical, chemical, and biological properties of soils occupied by Western Montane forests and reported that biological properties of soil were more sensitive to heating than soil physical and chemical properties, as most of the microorganisms can survive at temperature below 100°C . Soil heating causes the alteration of microbial reproductive capacity and lysing of microbial cells. Grogan *et al.* (2000a) studied the effects of wildfire ash on ectomycorrhizal associations by sampling bishop pine (*Pinus muricata*) seedlings from control and ash-removed plots 1.5 years after a severe fire in Northern Californian *P. muricata* forest. The below-ground community composition of ectomycorrhizal at the site was characterized using molecular techniques (PCR-RFLP and nucleotide sequencing) and they concluded that there were no significant effects of ash removal on plot-level mycorrhizal community richness or diversity, and there were no distinct treatment-related clusters in a principal components analysis. Moreover, comparison with pre-fire studies from similar *P. muricata* sites nearby indicated that severe wildfire disturbances resulted in marked changes in mycorrhizal community composition, and a sharp increase in the relative biomass of ascomycetous fungi.

Choromanska and DeLuca (2002) studied the effect of soil heating (160°C and 380°C) under three moisture regimes (-0.03, -1.0 and -1.5 MPa) on microbial activity and N mineralisation in two soils i.e. not exposed to fire for the past 80 years and recently exposed to wildfire and reported that initially the fire exposed soil had lower basal respiration rates and lower concentrations of microbial biomass C than the soil not exposed to fire.

Badia and Marti (2003) conducted an incubator experiment to study the effect of heating and ash deposition on microbiological properties in two arid soils (gypsiferous and calcareous soils) and concluded that biological status of gypsiferous soil and calcareous soil were affected differently by heating. Heating produced a significant decrease in basal respiration and biomass C of gypsiferous soil up to 150°C and drastically reduced these at 500°C. However, in calcareous soil, only the highest temperature of 500°C reduced basal respiration and biomass C.

Mabuhay *et al.* (2003) conducted a study in three different areas in Hiroshima prefecture, i.e. one unburned area and two burnt areas (one immediately after and one 2 years after fire) to determine the microbial biomass carbon and microbial abundance after fire and to establish relationships between microbial biomass and microbial abundance and the physico-chemical properties of the soil and reported that microbial biomass carbon and microbial abundance were highest in the unburned area followed by the area burnt two years ago and lastly by the area studied immediately after fire. Moreover, carbon biomass and microbial abundance were significantly correlated to the soil's physico-chemical properties such as pH, moisture content, water-holding capacity and C:N ratio.

Guerrero *et al.* (2005) conducted an experiment on Mediterranean forest soil and analysed the soil sample in a muffle furnace to seven temperatures (Ranging from 100-700°C) for 15 min to simulate different fire intensities and heated soils were incubated for 100 days after re-inoculation with fresh unheated soils to study the effect of heating on microbial recolonization and chemical changes in soil and concluded that the heating of soil decreased the total organic carbon, but increased the pool of soluble organic compounds. The released soluble organic carbon generally acts as readily metabolizable compounds for recolonizing microbes, results in increase in the population of microorganism, mainly heterotrophic bacteria. Moreover, soil samples exposed at 400°C had more microbial biomass (mainly bacteria) as compared to soil samples exposed to 200°C and 300°C.

Rutigliano *et al.* (2007) studied the impact of fire (low and high severity) on soil fungal abundance and microbial efficiency in C assimilation and mineralisation in a Mediterranean area of Southern Italy over 2 years after fire. They studied total and active fungal mycelium, microbial biomass C, percentage of microbial biomass C present as fungal C, metabolic quotient (qCO_2) and coefficient of endogenous mineralisation were determined and reported that fire significantly decreased the fungal mycelium whereas, it stimulated microbial growth probably through the enhancement of bacterial growth because of the increase in organic C and nutrient contents in burned plots. This shift in microbial community composition results in reduction in soil microbial efficiency of C assimilation (high qCO_2) and the increase in C mineralisation rate (CEM) in the first 84 days after fire.

Knelman *et al.* (2015) studied the effect of *Corydalis aurea*, a common post-fire colonizer plant species on soil chemistry, microbial biomass, soil enzyme activity and bacterial community structure one year after a major forest wildfire in Colorado, USA. In severely burned and lightly burned soils there were significant differences in soil edaphic and biotic properties resulting in increased per cent nitrogen, extractable organic C, microbial biomass, β -glucosidase enzyme activity and shifts in bacterial community diversity.

2.4 EFFECT OF FIRE ON PHYSICO-CHEMICAL AND BIOLOGICAL PROPERTIES

Coles and Morrison (1930) explained the decrease in pH after fire by pointing out that soil heating exposes new surfaces and dehydrates colloids, with the subsequent decrease in the soil buffer capacity. Inversely, when soil is exposed to temperatures higher than 700 °C the loss of OH^- groups from clay minerals and formation of oxides caused by the carbonate disruption can account for pH decrease. Isac and Hapkins (1937) reported that slash burning after logging caused the loss of an equivalent of 450 kg ha⁻¹ N from the site. They also found that organic matter reduced one-third by burning in the top three inches, while below that the changes were found non-significant.

Ahlgren and Ahlgren (1965) studied the effects of prescribed burning on soil microorganism in a Minnesota jack pine forest by using soil dilution plate counts on selective media for bacteria, streptomyces and fungi at intervals before and after two prescribed burns on 10-acre jack pine tracts and reported that the number and activity of most microorganisms decreased immediately after fire but rose abruptly to a very high level after the first rainfall

following burning. This increase is believed to be caused by the leaching of ash minerals. With special reference to soil colour, Brown and Davis (1973) reported that burning removes the shade of vegetation thereby increasing the solar radiation influx and blackening of soil due to absorption of more heat which further increased the soil temperature.

Widden and Parkinson (1975) studied the effects of a forest fire on soil microfungi in a *Pinus contorta* forest in Alberta, where it was found that species of *Trichoderma* and *Penicillium* were reduced in the burned plot, whereas, *Gelasinospora* sp. occurred only in the burned plot and *Cylindrocarpon destructans* appeared not to be affected by fire. DeBano and Conrad (1978) reported that total phosphorus increased by 300 per cent in the two months following the fire and suggested that all phosphorus in plants and litter was added to the soil as ash.

In studies on the effects of burning cereal straw to determine the long- and short-term effects on wheat yields and soil properties of chernozemic soils Biederbeck *et al.* (1980) suggested the frequent fires led to decreased mineralization as a result of reductions in pools of readily decomposable C and N and resultant decrease in microbial biomass. Moreover, bacterial and fungal populations decreased immediately and substantially only in the top 2.5 cm of soil upon burning, with the fall burn being more detrimental than spring burn. Repeated burnings in the field permanently diminished the bacterial population by more than 50 per cent, whereas, the fungi appeared to recover.

Kang and Sajjapongse (1980) studied the effect of heating on the properties of Apomu, Egbeda and Gambari surface soils of Southern Nigeria under laboratory conditions. They found that heating at low temperatures ($\leq 100^{\circ}\text{C}$) has no detrimental effect on soil properties, whereas, it increased the soil extractable P, Mg, Fe, Mn and Zn levels. Pronounced reductions in total N, Org. C, Org. P and extractable Ca and Mg levels and marked increase in extractable P, Zn, Mn and Fe were observed by heating to 200°C . Heating to $\geq 500^{\circ}$ had an adverse effect on soil chemical and physical properties. Mroz *et al.* (1980) studied the effect of burning on N loss in Red pine, Hemlock and Douglas fir and estimations done immediately after burning showed total and available N losses from the O-horizon, but gain in total N was found in underlying layers. Theodorou and Bowen (1982) found that after four weeks of a bushfire of moderate intensity an increase in microbial numbers in the burned soil occurred as compared to control. They explained such an increase

by considering that pH rose from 4.6 to 5.8 and the mild heat released easily-available energy sources from the soil organic matter.

Khanna and Raison (1986) studied the effect of fire intensity on solution chemistry of surface soil under a *Eucalyptus pauciflora* forest at three different sites which were unburnt forest, areas prescribed burnt resulting in almost complete canopy scorch, and ashbeds (intensely heated soil) and concluded that large quantities of cations (Ca^{2+} , Mg^{2+} , K^+ , NH_4^+) and anions (Cl^- , SO_4^{2-}) and soluble silica were mobilized by burning, especially under ashbeds. After burning, Ca^{2+} became the dominant cation in saturation extracts of surface (0-5 cm) soils for the entire three year study period. Moreover, in the 5-15 cm soil layer, firstly NH_4^+ and later K^+ replaced some of the Na^+ in the solution phase and most of the Cl^- deposited in ash was leached below 15 cm depth within one year and was probably accompanied by transport of K^+ , Mg^{2+} , Na^+ and NH_4^+ but very little transfer of Ca^{2+} occurred. Kutiel and Naveh (1987) reported that fourteen months after the fire, the organic matter and nutrient levels in the burned soil were less than those of the unburned soil. The exception was total phosphorus which was significantly higher in the upper, burned, soil layer than in the unburned. At the same time, all soil parameters measured were higher in the upper layer (0-5 cm) than in the lower one (5-25 cm). In another studies, Rashid (1987) reported that pH increased sharply in the burned surface soil (0-5 cm) taken five months after the fire and dropped only by half a unit over 14 to 21 months. However, at greater depth (5-15 cm) the burned soil was more acidic than the adjacent unburned soil up to nine months following the fire and thereafter its pH rose only slightly above that of the unburned soil.

Dhillion *et al.* (1988) studied the effect of fire on mycorrhizal ecology of blue stem and found that colonization levels of VAM fungi in little bluestem roots were significantly reduced on burned sites as compared to unburned sites, but increased significantly after one growing season. Their results suggested that the response of VAM fungi to fire may be attributed to changes in the host plant rather than the direct effect of fire. Similarly, Klopatek *et al.* (1988) studied the effects of fire on vesicular-arbuscular mycorrhizal fungi using microcosms constructed from soil, litter, and duff collected beneath canopies of pinyon pine, Utah juniper, and in the open space (interspace), where burning was conducted over wet and dry soils and reported that plants grown in soils burned when dry had a lower VAM colonization than soils burned when wet. Moreover, juniper soils demonstrated the greatest reduction compared to their respective controls and plants grown in interspace soils burned

when wet were least affected. There was a positive correlation between the decrease in VAM colonization and soil temperature as a result of fire.

Kutiel and Shaviv (1989) while working on effect of burning in oak and *Pinus halepensis* forest, reported that available P increased significantly right after the burning while EC increased slightly after burning owing to the release of soluble cations such as Ca, K and Mg. Klopatek *et al.* (1990) studied nitrogen transformations in pinyon-juniper ecosystems resulting from burning and reported immediate increase in soil NH_4^+ , decreasing with depth. The greatest increases were noted in both the pinyon and juniper soils that were dry at the time of the burn. Ninety days after the burn microbial biomass N was highest in the controls, followed by the wet and then the dry-burned soils, in both the pinyon and juniper microcosms. This was inversely related to the levels of accumulated NO_3^- .

Marion *et al.* (1991) studied the effect of fire severity, ash deposition and clipping effects on soil nutrients of eight experimental treatment designs in Chaparral and reported that fire severity affected both the quality and quantity of ash. Increasing fire severity increased the concentrations of Mg and K and decreased the concentrations of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ in the ash. As fire severity increased, there was an increased recovery of ash relative to standing biomass. Fire increased the availability of all nutrients ($\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, $\text{PO}_4^-\text{-P}$, Ca, Mg and K). This nutrient enhancement was largely restricted to the surface soil (0-5 cm) and only soluble N appeared to increase in the subsurface soil (5-10 cm). Clipping had no effect on enhancing soil nutrient availability. The apparent recovery of the basic cations in the water extracts of the ash samples was in the order: $\text{K} > \text{Mg} > \text{Ca}$ and this was different from the subsequent recovery in the soil: $\text{Ca} > \text{K} > \text{Mg}$.

Vilarino and Arines (1991) examined a forested ecosystem in Spain, a year following a wildfire, and found lower soil propagule densities and lower VAM colonization in post-fire herbaceous vegetation than in neighbouring unburned areas, although they had no information on the VAM distribution or activity prior to the fires. They further suggested that VAM are negatively affected by fire and mycorrhizal recovery in forested ecosystems is a slow process. Imeson *et al.* (1992) reported that the main effect of fire on soil physical properties is to eliminate the storage capacity of water in the organic horizons. Firstly infiltration rates remains higher but later on, it decreases due to the decrease in soil porosity.

Bauhus *et al.* (1993) found that fire could promote autotrophic bacteria over chemotrophic bacteria because of the soil enrichment in mineral salts. They also found a higher bacteria/fungi ratio in burned soil caused by the rise in pH after fire. Moreover, autotrophic nitrifiers were active only in surface ashbed soils and probably in limed soils. Kutiel and Inbar (1993) studied the impacts of fire on soil nutrients and soil erosion in a Mediterranean pine forest plantation in Israel and concluded that the soil nutrient content in the burnt plot was increased significantly whereas, runoff and erosion rates were low in both plots. However, on the burnt plot they were lower than on the unburnt plot, due to increased infiltration capacity. These results suggest that light and moderate forest fires may increase soil fertility without causing a marked difference in soil runoff and erosion.

Ulery and Graham (1993) studied the burned and unburned soils from an oak woodland and four mixed conifer sites to determine the effect of fire on soil colour and texture and reported that after severe burning, a 1 to 8 cm thick reddened layer formed at all of the sites, which was redder in hue and had higher chromas values than the unburned soils and underlying this layer was a blackened layer with a thickness of 1 to 15 cm and lower Munsell values. Moreover, the reddened soil layers had significantly less clay than either the unburned soils or blackened layers. Ulery *et al.* (1993) also studied the effect of intense burning on composition and mineralogy of wood-ash and soil pH of five sites in California and reported that soil pH increased by as much as 3 pH units (to pH 10.5) immediately after burning compared with unburned soil. Approximately 1 to 2% of each burn area was affected to a maximum observed depth of 20 cm and the major component of fresh, white wood-ash is calcite while K and Na carbonates are present in minor amounts. Moreover, the initial very high pH values of wood-ash and surface soil are caused by K and Na oxides, hydroxides, and carbonates. These compounds were found very soluble and did not persist through the wet season and calcite was much less soluble and was present in soils 3 years after burning maintaining moderately alkaline pH in surface soils which were normally neutral to strongly acid.

Naidu and Srivasuki (1994) studied the influence of forest fire on soil characteristics in different areas of Seshachalam hills. The effect of forest fire was more pronounced in 0-20 cm depth of the soil. Fire caused marked decrease in its water holding capacity (15, 25 per cent), organic carbon (0.33, 0.55 per cent), phosphorus (3.7, 8.1 kg ha⁻¹) and nitrogen (276, 498 kg ha⁻¹) content and increase in pH (8.0,6.8), EC (0.24,0.15) and potassium

content (154.12 kg ha⁻¹) respectively. Ojima *et al.* (1994) studied the long and short-term effects of fire on nitrogen cycling in tallgrass prairie and found that in the short-term, fire in the tallgrass prairie enhanced microbial activity, increased both above-and belowground plant production, and increased nitrogen use efficiency (NUE). However, repeated annual burning results in greater inputs of lower quality plant residues causing a significant reduction in soil organic N, lower microbial biomass, lower N availability, and higher C:N ratios in SOM. Changes in amount and quality of below-ground inputs increased N immobilization and resulted in no net increases in N availability with burning.

Romanya *et al.* (1994) studied soil P fractions and P sorption-desorption characteristics by extracting the soils with Bray 1 extractant seven months after clear felling and slash burning at a mixed eucalyptus forest site in Eastern Australia and concluded that the effects of fire on soil P were greatest in the surface soil horizons and depends upon fire intensity. Ash bed soils differed from unburnt soils for P fractions and P sorption and desorption characteristics. Labile inorganic P (Bray I) increased from less than 1 mg kg⁻¹ in the unburnt soil to 5-13 mg kg⁻¹ in the ash bed. Inorganic P (NaOH and H₂SO₄ extractions) increased markedly after fire, especially in the surface layers. After incubation for two months, labile organic P in the unburnt soil increased, whereas large decline were observed in ashbeds and surface (0-5 cm) burnt soils.

Dumontet *et al.* (1996) studied the post-fire changes soil nutrient content of a pine forest soil from a mediterranean environment and reported that C, N and P contents of soil surface layer were greater one year after a fire and declined in soils as time since the last fire increased. After eleven years, the soil nutrient content and the size of the microbial biomass were still lower than the neighbouring unburnt site suggested that forest fires have a long-term effect on soil microbiological properties. Hernandez *et al.* (1997) evaluated the short-term effect of wildfire on the chemical, biochemical and microbiological properties of Mediterranean pine forest soils and reported that all burnt soils had higher contents of nitrates, exchangeable NH₄⁺ and available P and K while their contents of total organic C, extractable C, humic acids, water-soluble C and total water-soluble carbohydrates were lower than those of unburnt soils. Microbial biomass-C in burnt soils represented from 50 per cent to 79 per cent that of unburnt soils.

Torres and Honrubia (1997) studied the effects of a natural fire on ectomycorrhizal inoculum potential of soil in respect of the number of sclerotia in soil, and the percentages and types of mycorrhizas present in mediterranean forest of *Pinus halepensis* in and found that fire causes a particularly marked decrease in basidiomycetes and a selective enrichment of species typically carbonicolous among ascomycetes. Moreover, the number of sclerotia in burned stands was greater than in unburned stand. Hauer and Spencer (1998) also reported that N and P concentration increase during fire, but trend to decreases after sometime of fire.

Marafa and Chau (1999) evaluated the effect of hill fire on soil chemical properties of two sites viz. new burnt site and old burnt site. On new burnt site soil pH increased by 0.27 to 0.33 units and exchangeable N and K by over 100 per cent, but had reduced total exchangeable acidity by 75 per cent, NH_4 by 42 per cent, total P by 66 per cent, exchangeable Na by 42 per cent compared with old burnt site. On the other hand, Newland and DeLuca (2000) investigated the effect of fire exclusion and reintroduction of fire on the frequency, occurrence, and function of native N-fixing plant species at eleven paired burnt and unburnt sites of ponderosa pine-Douglas-fir forests in Western Montana and they reported that the percent cover of N-fixing plants was low at all sites, the cover and frequency of N-fixing plants were significantly greater in sites exposed to fire than in the unburned sites and greater in repeatedly opened sites than in undisturbed sites. In contrast, levels of available N were significantly lower in burned sites compared with unburned sites and in repeatedly opened sites.

Rikhari and Palni (1999) reported increase in soil pH, total organic carbon, total P and total K after burning at Garhwal, however, total N decreased after burning. Stendell *et al.* (1999) studied the effect of fire on total ecto-mycorrhizal biomass. Their study concluded that the total ecto-mycorrhizal biomass in the unburned plots did not differ for any core layer, while in the burnt site, there is an eight-fold reduction in the total ecto-mycorrhizal biomass due to the destruction of litter organic layer.

Ketterings and Bigham (2000) studied the effects of fire on various soil physical properties and soil fertility and concluded that the effects are mainly because of burn severity and changes in soil colour and texture are most noticeable in severely burned soils in comparison to nearby slightly or moderately burned soil. At higher temperature reddening of soil matrix occurs. Redder hue appears in the burned soils due to the transformation of Fe-

oxides and complete removal of organic matter. Moreover, soil exchangeable Ca, Mg, and K increased with fire severity, while exchangeable acidity and Al decreased 2 week after the burn. Soil C and N were reduced at high burn severity only. Phosphorus showed an increase in availability at low to medium fire severity and a decrease in availability at the most intense burn levels.

Grogan *et al.* (2000b) examined the influence of wild-fire ash residues on soil, microbial and plant N pools in a recently burned Californian bishop pine (*Pinus muricata* D. Don) forest. Ash stimulated post-fire primary production and ecosystem N retention through direct N inputs from ash to soils as well as indirect ash effects on soil N availability to plants. Their results suggested that redistribution of surface ash after fire by wind or water may cause substantial heterogeneity in soil N availability to plants. Moreover, at the burned site, ^{15}N natural abundance in recolonising species was similar to that in bulk soil organic matter. By contrast, there was a marked ^{15}N depletion in the same species relative to the total soil N pool at the unburned site. Grogan *et al.* (2000a) also studied the effects of wildfire ash on ectomycorrhizal associations by sampling bishop pine (*Pinus muricata*) seedlings from control and ash-removed plots one and half years after a severe fire in Northern Californian *P. muricata* forest. The below-ground community composition of ectomycorrhizal at the site was characterized using molecular techniques (PCR-RFLP and nucleotide sequencing) and they concluded that there were no significant effects of ash removal on plot-level mycorrhizal community richness or diversity, and there were no distinct treatment-related clusters in a principal components analysis. Moreover, comparison with pre-fire studies from similar *P. muricata* sites nearby indicated that severe wildfire disturbances resulted in marked changes in mycorrhizal community composition, and a sharp increase in the relative biomass of ascomycetous fungi.

DeBano (2000) studied the effects of fire on nutrient cycling, physical, chemical, and biological properties of soils occupied by Western Montane forests and reported that biological properties of soil were more sensitive to heating than soil physical and chemical properties, as most of the microorganisms can survive at temperature below 100°C. Soil heating causes the alteration of microbial reproductive capacity and lysing of microbial cells. Guinto *et al.* (2001) studied the long-term impacts of repeated prescribed-burning on surface (0-30 cm) soil chemical properties and forest floor nutrients in two contrasting native eucalypt forests in South-East Queensland, Australia and reported that at the dry sclerophyll

site, more than forty years of annual burning had not led to any loss in topsoil total nitrogen and organic carbon but had significantly increased topsoil acid-extractable phosphorus. At the wet sclerophyll site, biennial burning (10 burns) resulted in decreased in topsoil total nitrogen and potentially mineralisable nitrogen despite a shorter experimental period (twenty two years).

Knoepp *et al.* (2004) in studies on the effect of fell and burn treatment applied to three mixed oak–pine stands in the Nantahala National Forest in Western North Carolina and determined the effects of this treatment on soil nutrient availability and potential nutrient loss. Exchangeable soil cations, pH, total carbon (C), and total nitrogen (N) were measured before and periodically for five years after treatment and they reported that exchangeable calcium and magnesium concentrations, soil pH, and N availability increased after burn treatment. There was no treatment effect on total soil C or N. Nitrogen mineralization rates were greater on burned versus control plots in 50 per cent of the post-treatment measurements.

Alauzis *et al.* (2004) studied the long-term effects of wildfire on the mineralogical, physical, chemical and biological properties of a soil developed from volcanic-ashes under *Nothofagus pumilio* forests and reported a significant increase in pH, electrical conductivity, extractable P and cations (Ca, Mg, Na, K) and a significant decrease in organic C and total N and decrease of 31 per cent in field capacity and 56 per cent in soil moisture. Certini (2005) reported that bulk density of soil increases after the fire because of collapse of aggregates and clogging of voids by the ash and dispersed clay minerals. As a result, soil porosity and permeability decreased. He also reported that fire can influence a variety of soil physical and chemical properties including the loss of structure, reduction in organic matter of soil, reduced porosity and increased pH. The wide range of effects of fire on soil properties are due to the inherent pre-burn variability in these resources, fire behaviour characteristics, season of burning, and pre-fire and post-fire environmental conditions such as timing, amount, and duration of rainfall. These changes can cause various indirect effects such as increased hydrophobicity, which results in decreased infiltration and increased run-off which ultimately results in increased soil erosion.

Neary *et al.* (2005) studied the effects of fire on soil texture and concluded that the most sensitive textural fraction was clay, which begins changing at soil temperature of about 400°C when clay hydration and clay lattice structure begin to collapse. At temperature of 700-800°C complete destruction of internal clay structure can occur.

Neff *et al.* (2005) conducted an experiment on effects of fire on soil organic matter content, composition, and nutrients in boreal interior Alaska and found that one year after the wildfire, burned soils contained between 1071 and 1420 g/m² less carbon than unburned soils. Burned soils had lower nitrogen than unburned soils, higher calcium, and nearly unchanged potassium, magnesium, and phosphorus stocks. Moreover, the chemistry of deeper soil layers in burned and unburned sites was similar, suggesting that immediate fire impacts were restricted to the surface soil horizon. Molina *et al.* (2007) and Schafer and Mack (2010) reported that soil pH generally increased after fire because of the presence of ash due to the high pH of ash. Nadel *et al.* (2007) studied the effect of fire on nutrient dynamics and invertebrate faunal composition in a *Eucalyptus grandis* plantation in South Africa. The *in situ* nitrogen and phosphorus mineralization rates and invertebrate faunal composition were measured in six sites i.e. three burned and three unburned prior to and after a low-intensity fire and the study revealed that within the burned plots, phosphorus availability was enhanced 10-fold within the first month following the fire. Invertebrate faunal diversity was low both prior to and after burning.

Cerda and Doerr (2008) also investigated the effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period in the Sierra de la Calderona (Valencia province, eastern Spain) and reported that bulk density increased substantially with ash depth. Bulk density increases because of collapse of aggregates and clogging of voids by the ash and dispersed clay minerals; as a consequence, soil porosity and permeability decreases.

Tufekcioglu *et al.* (2010) evaluated the effect of prescribed burning on soil properties in young Corsican pine (*Pinus nigra* Arn.) stands in Turkey and found that soil pH was significantly higher in burned sites than in control sites, in 15-35 cm soil depth, and there was no significant difference in pH between control and burned sites for the 0-15 cm soil depth. Aref *et al.* (2011) investigated the effect of forest fire after one year in three natural forests in Al Baha region (south-west Saudi Arabia) and concluded that fire had no effect on soil texture. Soil pH increased significantly, whereas, EC significantly decreased in the burnt sites as compared to unburnt areas. Organic matter and total N decreased significantly in the burned areas whereas available P and K increased significantly after fire. Fires consume N from plants and surface soil layer, resulting in a reduction of N pool in burned forest (Hyodo *et al.*, 2013).

2.5 COMPARATIVE EFFECTS OF FIRES ON SOIL PROPERTIES UNDER DIFFERENT LAND USES

Rau *et al.* (2007) studied the effects of prescribed fire, vegetation type and time of following fire on soil KCl, extractable nitrogen and NaHCO₃ extractable phosphorus in a pinyon–juniper woodland and its associated sagebrush ecosystem, immediately before and for four years after a spring prescribed burn. Potassium chloride extractable NH₄⁺ and total inorganic-N increased immediately following prescribed fire, whereas, extractable NO₃⁻ decreased immediately after the burn. In the surface layer (top 8 cm), extractable NH₄⁺ remained elevated compared to the control through year two after the burn. Moreover, by the first post-burn extractable NO₃⁻ and total extractable inorganic-N increased and remained elevated over the control through three years after the burn in the surface layer. For the entire soil profile (52 cm), the fire had no effect on NH₄⁺ and the effects on total extractable inorganic-N were no longer significant after one year. However, NO₃⁻ remained elevated over the control through year two post-fire for the soil profile.

Marti-Roura *et al.* (2011) conducted an experiment on impact of fire and drought on soil organic carbon under Mediterranean shrublands and grasslands in the north-eastern Iberian Peninsula and reported short-term increase in organic C just after the fire and this increase was greater in soils from mixed shrub-grasslands and shrublands than in soils from the pure grasslands. They also showed that organic C was higher at the soil surface than in sub-surface layer.

Nigussie and Kissi (2011) investigated the impact of biomass burning on soil properties by collecting composite and core soil samples at a depth of 0-20 cm from cultivated land, a charcoal production site, and farmlands in Jimma Zone, Southwestern Ethiopia and found that burning of biomass significantly decreased bulk density and clay percentage while the sand fraction was increased significantly. However, the differences in silt percentage and WHC were non-significant. Burning also increased pH, EC, available phosphorous, CEC (cation exchange capacity), and exchangeable bases significantly as compared to cultivated land. Furthermore, charcoal production significantly increased organic carbon and total nitrogen, but burning of crop residues for land preparation reduced them significantly.

Bhuyan *et al.* (2014) studied the effect of season, soil and land-use pattern on soil N-mineralisation, ammonification and nitrification in home garden and paddy AES (agro-

ecological situations) in East Siang District of Arunachal Pradesh and recorded greater amount of N-mineralization during the rainy season in both the land use patterns. Moreover, ammonification rate was positively correlated with soil pH, SOC, NH_4^+ -N and NO_3^- -N whereas nitrification rate was negatively correlated to ammonium and nitrate concentration.

Chapter - 3

MATERIALS AND METHODS

The present investigation entitled “**Effect of fire on mineralization of soil organic matter**” was carried out at four sites located at Dr. Y.S. Parmar University of Horticulture and Forestry Nauni, Solan, Himachal Pradesh, during the year 2018 – 2019, with an aim to determine the effect of fire on net nitrogen mineralization, organic carbon and microbial biomass carbon. This chapter presents the analytical tools and methods employed to achieve the specific objectives under the following different sections and sub-sections:

- 3.1 General description of the study area**
- 3.2 Experimental Details**
- 3.3 Collection and preparation of soil samples**
- 3.4 Soil analysis**
- 3.5 Interpretation of data**
- 3.6 Statistical analysis**

3.1 GENERAL DESCRIPTION OF THE STUDY AREA

3.1.1 Location

The experimental site comprised of the general chirpine plantations and its adjoining areas under the Department of Silviculture and Agroforestry, in the vicinity of College of Forestry, Dr. Y S Parmar University of Horticulture and Forestry, Nauni, Solan (HP). The area is situated at 30°52' North latitude and 77°11' East longitude, at an elevation of about 1260 m above mean sea level and representing the mid hill zone of Himachal Pradesh.

3.1.2 Climate

The study area falls under the sub-temperate, sub-humid agro-climatic zone-II of Himachal Pradesh. The average annual rainfall of the area is about 1115 mm and about 75 per cent of it is received during the monsoon period (mid-June to mid-September). Winter rains are meagre and received during the month of January and February. May-June are the hottest and December-January are the coldest months.

3.1.3 Topography and soil

The study sites are marked by an undulating topography with well developed drainage system. Geologically, the area has been reported to be a part of the outer Himalayas. The soil is derived from inferakasol, series of rocks mainly of Shimla groups comprised of carbonaceous shales, calcareous shales, dolomitic limestone with bands of intermittent shales (Rao, 1998). The soil under tree/grass vegetation are particularly shallow with very poorly developed loamy texture and sizeable portion of stony material. The soils of the study area fall in the order Inceptisol and sub group Eutrochrept according to Soil Taxonomy of USDA. These soils owe their origin to ferromagnesian shales and dolomitic limestone.

Table 3.1: Initial values of Ammonical-N (mg kg^{-1}), Nitrate-N (mg kg^{-1}) and Microbial biomass C ($\mu\text{g g}^{-1}$ soil) under different land uses prior to the initiation of fire

Depths Properties and Land uses	0-5 cm	5-10 cm	10-15 cm
Ammonical-N			
Chir pine forest	93.78	91.6	89.60
Grassland	83.57	82.14	81.52
Scrubland	82.60	81.30	80.70
Unburnt chir pine	93.78	91.60	89.60
Nitrate-N			
Chir pine forest	51.20	54.60	51.80
Grassland	49.30	53.80	51.60
Scrubland	50.20	53.10	50.70
Unburnt chir pine	51.20	54.60	51.80
Microbial biomass C			
Chir pine forest	177.23	174.18	171.46
Grassland	155.78	151.42	146.31
Scrubland	152.34	149.61	145.68
Unburnt chir pine	177.23	174.18	171.46

3.2 EXPERIMENTAL DETAILS

For carrying out the present studies a thorough survey of Chir pine plantations, pure grasslands and scrubland within and around the University area was done. Out of the number of sites available, finally four representative sites depicting three different ecosystems and a control of non- fire chir pine site were selected within the University area as under:

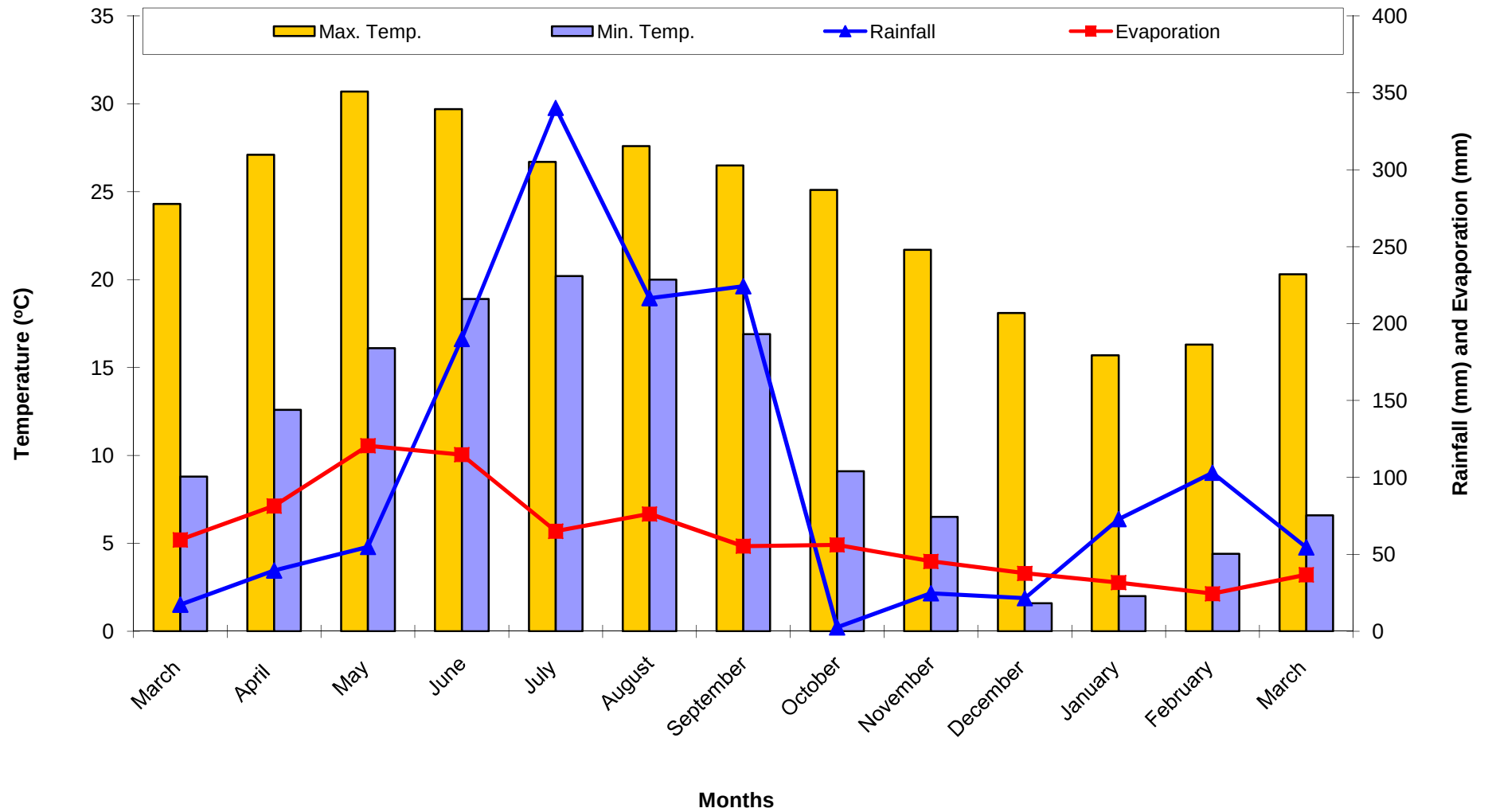


Fig. 3.1 Agro-meteorological data of the study area (March 2018 – March 2019)



Plate 3.1 Controlled fire in the study area

Land Use 1	-	Chir pine forest
Land Use 2	-	Grassland
Land Use 3	-	Scrubland
Land Use 4	-	Unburnt chir pine (control)
Depths	:	3 (0-5 cm, 5-10 cm and 10-15 cm)
Number of Replications	:	5 (5 locations)

1. College of Forestry
2. Below Department of Soil Science
3. Old Farmers' Hostel
4. Nauni above Officers' residences
5. Near Girls Hostel

Design: Randomized Block Design (factorial)

3.3 COLLECTION AND PREPARATION OF SOIL SAMPLES

Soil samples were taken before the start of the experiment in the month of March, 2018 at three soil depths (0 to 5 cm, 5 - 10 cm and 10-15 cm) from a plot size of 50m× 50m for each land use at each site. The soil samples were dried in shade and then crushed in a wooden pestle and mortar. The samples were then passed through a 2 mm sieve and stored in polythene bags for their subsequent analysis. A controlled fire was done in all the selected land uses after the collection of initial soil samples in the month of March, 2018, including in the Chir Pine area. After the fire, the soil samples were collected at monthly intervals (from April, 2018 to March, 2019) for the study of soil carbon and net nitrogen mineralization. For analysis of microbial properties the unprocessed samples were used.

3.4 SOIL ANALYSIS

The soil samples collected prior to fire treatment were further analysed for different parameters like texture, pH, electrical conductivity (EC), organic carbon (OC), bulk density and available N, P and K before and after the experiment. For nitrogen mineralisation, soil microbial biomass carbon and status of organic carbon samples collected at monthly intervals were analyzed. The soil analysis was done as per the procedures described below:

3.4.1 Soil texture

The soil texture of the soil was determined by the Hydrometer method (Bouyoucos, 1927).

3.4.2 Bulk density

The bulk density of the unprocessed soil in the field was estimated with the core sampler method (Black, 1965).

3.4.3 Soil pH

Soil pH was measured by digital pH meter by mixing soil and water in the ratio of 1:2, as per the method detailed by Jackson (1973).

3.4.4 Electrical conductivity

Electrical conductivity of the soil was measured in the supernatant of the soil: water suspension (1:2) at 25°C with digital microprocessor based conductivity meter, as per the method detailed by Jackson (1973).

3.4.5 Organic carbon

The soil organic carbon was determined by the rapid titration method given by Walkley and Black (1934) and subsequently the soil organic matter was calculated as:

Soil organic matter (%) = Organic carbon (%) $\times$ 1.724

3.4.6 Available macronutrient elements

- i. **Available nitrogen (kg ha^{-1}):** Available nitrogen was estimated with the help of the method given by Subbiah and Asija (1956). 20 gram of soil was weighed and moistened with distilled water. Then, the weighed soil was added to distillation flask and 100 ml of 0.32 percent KMnO_4 and 100 ml of 2.5 percent NaOH were added to the distillation flask and cork was fitted immediately. 25 ml of N/50 H_2SO_4 was taken in a conical flask and 2-3 drops of methyl red indicator were added to the conical flask. After the setup was complete, the heater was switched on and 25-30 ml of distillate was collected in the same conical flask containing N/50 H_2SO_4 . The excess of H_2SO_4 collected in the conical flask was titrated against N/50 NaOH and change in colour from pink to yellow was noted as the end point.
- ii. **Available phosphorus (kg ha^{-1}):** Available Phosphorus was extracted by sodium bicarbonate (pH 8.5) and further determined by Olsen method (Olsen *et al.* 1954). By the stannous chloride reduced ammonium molybdate method the blue colour intensity was measured on the spectrophotometer at 660 nm keeping blank appropriately. Available P was then expressed as kg ha^{-1} .

- iii. **Available potassium (kg ha^{-1}):** Available potassium was extracted with neutral normal ammonium acetate method (Mervin and Peech, 1951), and the K content in the filtrate was determined on the flame photometer. The reading was noted and expressed in kg ha^{-1} .

3.4.7 Ammonical and Nitrate nitrogen

Ammonical N was estimated by using MgO Deverda's alloy method, where soil was extracted with potassium chloride and then direct analysis by steam distillation. Nitrate- N was estimated using colorimetric method, where soil was extracted with extracting solution containing copper sulphate and silver sulphate (Ho, 1984).

3.4.8 Net mineralization

The net mineralization over a period of one month (per month basis) was calculated by simple subtraction of $\text{NO}_3\text{-N} + \text{NH}_4\text{-N}$ final values from their initial values, and the net increase in $\text{NO}_3\text{-N}$ and $\text{NH}_4^+ \text{-N}$ was used to indicate net nitrification and ammonification, as suggested by Durán *et al.* (2009) in a forest ecosystem.

3.4.9 Mineralization rate

The soil mineralization rate was estimated by adopting the formula given by Zhou and Ouyang (2001):

Soil net mineralization rate and soil net nitrification rate were calculated as following:

$$Nmin=(N_2-N_1)/d$$

Where, $Nmin$ is soil net N mineralization rate ($\text{mg kg}^{-1}\text{d}^{-1}$), N_1 is the initial inorganic N content ($\text{NH}_4\text{-N} + \text{NO}_3\text{-N}$) before incubation, N_2 is the final inorganic N content ($\text{NH}_4\text{-N} + \text{NO}_3\text{-N}$) after incubation; d is the incubation days (d)

3.4.10 Microbial biomass carbon

Microbial biomass carbon was determined by soil fumigation- extraction method as detailed by Vance *et al.* (1987). In this method, 10g of soil was fumigated with 20 ml of CHCl_3 in vacuum desiccators for 24 hours in dark, and other 10g of same soil sample was refrigerated, then both the samples (fumigated and unfumigated) were extracted with 0.5 M K_2SO_4 for half an hour and then the extract was treated with H_2SO_4 and orthophosphoric acid and heated on hot plate at 120°C for 30 minutes. The resultant material was diluted to 250 ml with distilled water and 2-3 drops of ferroin indicator was added and titrated against 0.005 N FAS (Ferrous Ammonium Sulphate) and calculated by $\text{MB-C } (\mu\text{g g}^{-1} \text{ soil}) = \text{OC}_F - \text{OC}_{UF} / K$ where,

OC_F = Total amount of EC (Extractable C) in fumigated soil

OC_{UF} = Total amount of EC (Extractable C) in unfumigated soil

K = Factor (0.45)

3.5 INTERPRETATION OF RESULTS

The results on different soil parameters were interpreted by using the following critical limits:

Table 3.2: Critical limits of available nutrient elements in soils

Nutrient Elements	Soil fertility classes			References
	Low	Medium	High	
Organic carbon (% and g kg ⁻¹)	< 0.5 % (< 5.0 g kg ⁻¹)	0.5-1.0% (5.0-10.0 g kg ⁻¹)	>1.0% (>10.0 g kg ⁻¹)	Bhandari and Tripathi (1979)
Available N (kg ha ⁻¹)	<280.0	280.0-560.0	>560.0	FAI (1977)
Available P (kg ha ⁻¹)	<10.0	10.0-24.6	>24.6	FAI(1977)
Available K (kg ha ⁻¹)	<118	118- 260.0	>260.0	FAI (1977)

3.6 STATISTICAL ANALYSIS

Analysis of variance was done as per the model suggested by Panse and Sukhatme (2000). The data recorded was analysed using MS-Excel, OPSTAT and SPSS 16.0 package as per design of the experiment:

Analysis of variance (ANOVA) was calculated as follows:

Source of variation	Degree of freedom	Sum of squares	Mean sum of squares (M)	F _{cal.}
Replications	(r-1)	S _r	$\frac{\sum_{r=1}^r \sum_{t=1}^t \sum_{a=1}^a \sum_{b=1}^b Y_{rtab}^2}{(r-1)} = \frac{Mr}{r-1}$	M _r /M _e
Treatments	(t-1)	S _t	$\frac{\sum_{t=1}^t \sum_{r=1}^r \sum_{a=1}^a \sum_{b=1}^b Y_{rtab}^2}{(t-1)} = \frac{Mr}{t-1}$	M _t /M _e
Months (a)	(a-1)	S _a	$\frac{\sum_{a=1}^a \sum_{r=1}^r \sum_{t=1}^t \sum_{b=1}^b Y_{rtab}^2}{(a-1)} = \frac{Mt}{a-1}$	M _a /M _e
landuses (b)	(b-1)	S _b	$\frac{\sum_{b=1}^b \sum_{r=1}^r \sum_{t=1}^t \sum_{a=1}^a Y_{rtab}^2}{(b-1)} = \frac{Ma}{b-1}$	M _b /M _e
Months× Land uses interaction (a × b)	(a-1)(b-1)	S _{ab}	$\frac{\sum_{a=1}^a \sum_{b=1}^b \sum_{r=1}^r \sum_{t=1}^t Y_{rtab}^2}{(a-1)(b-1)} = \frac{Mab}{(a-1)(b-1)}$	M _{ab} /M _e
Error	(t-1) (r-1)	S _{tr}	$\frac{\sum_{r=1}^r \sum_{t=1}^t \sum_{a=1}^a \sum_{b=1}^b Y_{rtab}^2}{(r-1)(t-1)} = \frac{Ma}{(r-1)(t-1)}$	
Total	(tr-1)	S _(tr-1)		

where,

r	=	Number of replications
t	=	Number of treatments
a	=	Number of irrigation levels
b	=	Number of fertigation levels

The calculated 'F' values were compared with the tabulated 'F' values at 5 per cent level of significance. If the calculated value is higher than the tabulated, it has been considered significant.

The standard error of mean SE (m) and critical difference (CD) for comparing the means of any two treatments were calculated as below:

SE (m)	=	$\pm (Me/r)^{1/2}$
SE (d)	=	$\pm (2Me/r)^{1/2}$
Critical Difference (CD)	=	SE (d) $\times$ t (5%) value at error degrees of freedom

Chapter - 4

RESULTS AND DISCUSSION

The present investigation entitled “**Effect of fire on mineralization of soil organic matter**” was carried out at five sites taking four land uses, located at Dr. Y.S. Parmar University of Horticulture and Forestry Nauni, Solan, Himachal Pradesh, during the year 2018 – 2019. Data on different parameters were analyzed statistically and significance of results was verified. The results obtained with respect to the various parameters have been presented and discussed with possible explanations, under the following broad headings:

4.1 Soil properties under different land uses (Pre-fire)

4.1.1 Soil physico-chemical properties

4.1.2 Soil nutrient content

4.2 Nitrogen content of soil at monthly intervals after fire

4.2.1 Ammonical nitrogen (mg kg^{-1})

4.2.2 Nitrate nitrogen (mg kg^{-1})

4.3 Mineralization behaviour in soil after fire

4.3.1 Ammonification (mg kg^{-1})

4.3.2 Nitrification (mg kg^{-1})

4.3.3 Net mineralization (mg kg^{-1})

4.4 Changes in soil carbon after fire

4.4.1 Organic carbon (per cent)

4.4.2 Microbial biomass carbon ($\mu\text{g g}^{-1}$ soil)

4.5 Soil properties at the end of the experiment under different land uses

4.5.1 Soil physico-chemical properties

4.5.2 Soil nutrient content

4.1 SOIL PROPERTIES UNDER DIFFERENT LAND USES (PRE-FIRE)

Before the introduction of fire, composite soil samples were collected from different depths and different land uses and analysed for the physico-chemical properties as well as their nutrients content.

4.1.1 Soil physico-chemical properties

i. Soil texture

The soil texture of the experimental area was gravelly silty clay loam with sand (16.5 per cent), silt (48.2 per cent) and clay (33.4 per cent) the values of sand, silt and clay for the samples after twelve months did not vary much and remained almost the same.

ii. Bulk density (Mg m^{-3})

The results presented in Table 4.1, on the initial values of the soil physico-chemical properties under different land uses, shows that the bulk density of surface depth (0-5 cm) in forest soil was 1.11 Mg m^{-3} and it was found to increase to 1.14 Mg m^{-3} for 10-15 cm depth. In the grassland soil, the bulk density values for 0-5 cm, 5-10 cm and 10-15 cm depths were 1.14, 1.15 and 1.16 Mg m^{-3} , respectively. Similarly, for scrublands the initial values were 1.13, 1.14 and 1.16 Mg m^{-3} , respectively. The samples collected initially from the unburnt chir pine site did not vary from the fire site since the two sites were adjacent and samples collected from them were similar. In the unburnt chir pine site, the bulk density values were 1.11, 1.12 and 1.14 Mg m^{-3} , for the respective depths showing an increasing trend with soil depth. The lower values of bulk density in the surface layer is attributed to the higher organic matter content as well as root activity in these layers.

Table 4. 1: Soil physico-chemical properties under different land uses before the initiation of fire

Property Land use and Depth	Bulk density (Mg m^{-3})	pH (1:2)	EC (dS m^{-1})	Organic carbon (%)
Chir pine forest				
0-5 cm	1.11	5.91	0.467	1.23
5-10 cm	1.12	5.90	0.466	1.16
10-15 cm	1.14	5.91	0.464	1.14
Grassland				
0-5 cm	1.14	6.04	0.521	1.38
5-10 cm	1.15	6.03	0.520	1.22
10-15 cm	1.16	6.05	0.518	1.19
Scrubland				
0-5 cm	1.13	6.13	0.543	1.31
5-10 cm	1.14	6.11	0.541	1.22
10-15 cm	1.16	6.12	0.540	1.18
Unburnt chir pine				
0-5 cm	1.11	5.91	0.467	1.23
5-10 cm	1.12	5.90	0.466	1.16
10-15 cm	1.14	5.89	0.465	1.14

iii. Soil pH

The data on soil pH under different land uses before the initiation of fire (Table 4.1), shows that the soil pH values in forest soil were 5.91, 5.90 and 5.91 for 0-5 cm, 5-10 cm and 10-15 cm depth, respectively. In the grassland site, the soil pH value for 0-5 cm was 6.04, for 5-10 cm it was 6.03 and for 10-15 cm depth it was 6.05, respectively. Similarly, for scrublands the initial soil pH values for 0-5 cm, 5-10 cm and 10-15 cm depth were 6.13, 6.11 and 6.12, respectively. In the unburnt chir pine site, the initial soil pH values were 5.91, 5.90 and 5.89 for the respective depths. The soil pH did not vary much with the depth as well as between different land uses.

iv. Electrical conductivity (dS m^{-1})

An examination of the data presented in Table 4.1 shows that the EC of 0-5 cm in forest soil was 0.467 dS m^{-1} and it was found to decrease to 0.466 dS m^{-1} for 5-10 cm depth and 0.464 dS m^{-1} for 10-15 cm depth. The EC values for 0-5 cm, 5-10 cm and 10-15 cm depths in grassland were 0.521, 0.520 and 0.518 dS m^{-1} , respectively in the grassland site. Similarly, for scrublands the initial values were 0.543, 0.541 and 0.540 dS m^{-1} , for the respective depths. In the unburnt chir pine site, the values were 0.467, 0.466 and 0.465 dS m^{-1} , for the respective depths, showing decreasing trend with soil depth. As in the case of majority of the hill soils the electrical conductivity values were within the safe limits and also did not vary much with the land uses.

v. Organic carbon (per cent)

A perusal of the data presented in Table 4.1 reveals that the organic carbon in forest soil, was 1.23 per cent in 0-5 cm depth and it decreased with the increase in soil depth, i.e. 1.16 per cent and 1.14 per cent for 5-10 cm and 10-15 cm depth, respectively. Similarly, for grassland the initial values were 1.38, 1.22 and 1.19 per cent for 0-5, 5-10 and 10-15 cm depths, respectively. In the scrubland, the values were 1.31, 1.22 and 1.18 per cent for 0-5 cm, 5-10 cm and 10-15 cm depth, respectively. In the unburnt chir pine site, the initial organic carbon values were similar as that of chir pine in the fire site. It is also observed that the organic carbon of the grassland soils was higher as compared to the forest, as well as scrubland soils, which may be due to the higher root density in the surface layers of the grassland sites.

Table 4.2: Available N, P and K contents under different land uses before the initiation of fire

Property Land use and Depth	N (kg ha⁻¹)	P (kg ha⁻¹)	K (kg ha⁻¹)
Chir pine forest			
0-5 cm	296.2	25.2	272.7
5-10 cm	288.3	26.4	275.1
10-15 cm	272.4	24.3	273.4
Grassland			
0-5 cm	302.6	27.2	319.5
5-10 cm	291.4	29.5	321.5
10-15 cm	283.0	26.7	320.2
Scrubland			
0-5 cm	298.4	25.4	317.3
5-10 cm	287.3	27.3	320.2
10-15 cm	271.6	24.6	318.7
Unburnt chir pine			
0-5 cm	301.8	23.9	271.7
5-10 cm	296.4	26.1	275.3
10-15 cm	284.2	24.9	273.6

4.1.2 Available nutrient content in soil

i. Nitrogen (kg ha⁻¹)

The data pertaining to available nitrogen in soil before the fire, under different land uses, is enumerated in Table 4.2 and it shows that available nitrogen values were 296.2, 288.3 and 272.4 kg ha⁻¹ for 0-5 cm, 5-10 cm and 10-15 cm depth, respectively, in the forest soil. In the grassland, the available nitrogen values for 0-5 cm, 5-10 cm and 10-15 cm depth were 302.6, 291.4 and 283.0 kg ha⁻¹, respectively. The available nitrogen values were 298.4, 287.3 and 271.6 kg ha⁻¹ for the respective depths in the scrubland. In the unburnt chir pine site, the available nitrogen values were 301.8, 296.4 and 284.2 kg ha⁻¹ for the respective depths. The available N content in the chir pine forest as well as in other land uses did not vary much and all the soils analysed were found to be low in nitrogen.

ii. Phosphorus (kg ha⁻¹)

Appraisal of the data in Table 4.2 reflects that available phosphorus of surface depth (0-5 cm) in forest soil was 25.2 kg ha⁻¹ and it was found to decrease to 24.3 kg ha⁻¹ for 10-15 cm depth. In the grassland soil, the available phosphorus values for 0-5, 5-10 and 10-15 cm depths were 27.2, 29.5 and 26.7 kg ha⁻¹, respectively. The available phosphorus values for 0-5, 5-10 and 10-15 cm soil depths in scrubland were 25.4, 27.3 and 24.6 kg ha⁻¹, respectively

and in unburnt chir pine sites, they were 23.9, 26.1 and 24.9 kg ha⁻¹ for the respective depths. As in the case of nitrogen, the surface depth (0-5 cm) had a slightly lower nutrient content than the 5-10 cm depth, but it again decreased in the 10-15 cm depths. The available phosphorus content in the soils was slightly high.

iii. Potassium (kg ha⁻¹)

A scrutiny of the data presented in Table 4.2 reveals that available potassium before fire in forest soils was 272.7, 275.1 and 273.4 kg ha⁻¹ for 0-5, 5-10 and 10-15 cm depths, respectively. In the grassland soils, the available potassium in surface depth (0-5 cm) was 319.5 kg ha⁻¹ and 320.2 kg ha⁻¹ for 10-15 cm depth. In the scrubland, the initial values for 0-5, 5-10 and 10-15 cm were 317.3, 320.2 and 318.7 kg ha⁻¹, respectively. In the unburnt chir pine site, the available potassium values were 271.7, 275.3 and 273.6 kg ha⁻¹ for the respective depths. The available soil potassium content of all the land uses for all depths was medium. Also, the potassium content in chir pine forest was lower as compared to grasslands and scrublands.

4.2 NITROGEN CONTENT OF SOIL AT MONTHLY INTERVALS AFTER FIRE

A controlled fire was introduced in a 50× 50 m plot in the month of March 2018 and samples collected and analysed at monthly intervals after fire, keeping unburnt chir pine site as one of the land uses.

4.2.1 Ammonical nitrogen (mg kg⁻¹)

The data enumerated in Table 4.3 shows that the ammonical nitrogen content in the soils at 0-5 cm depth varied significantly with land uses as well as with advancing months post-fire. The maximum ammonical-N content of 102.85 mg kg⁻¹ was observed in the month of July, 2018 which was statistically at par with that of June, 2018 (101.47 mg kg⁻¹) and the minimum content (91.73 mg kg⁻¹) was observed after twelve months of fire i.e. March, 2019. Thus, when the fire was introduced, the ammonical-N increased in the first four months, thereafter showing a declining trend. In the forest land use, the results were significant and followed a similar trend with maximum ammonical-N content of 116.96 mg kg⁻¹ in July, 2018, and decreased continuously to 93.04 mg kg⁻¹ in March, 2019. When the different land uses were compared, it was observed that the maximum ammonical-N content was in the forest land use (105.11 mg kg⁻¹) which was significantly higher as compared to the other

three land uses, but the ammonical-N content of scrubland and unburnt chir pine site were found to be statistically at par. The interaction M×L shows that the maximum ammonical-N (116.96 mg kg⁻¹) was under forest land use in the month of July, 2018 and the minimum was 88.38 mg kg⁻¹ for scrubland in the month of March, 2019. The results shows that immediately after the fire, the ammonical-N content in all the land uses increased for the first few months and thereafter, it reduced and was found minimum after one year. When the values of ammonical-N were compared to the pre fire values (Table 3.1) of 93.8, 83.6, 82.6 and 93.8 mg kg⁻¹ for forest, grassland, scrubland and unburnt chir pine, respectively, it is observed that the ammonical-N in the fire plots increased significantly after the fire.

Table 4.3: Ammonical-N content (mg kg⁻¹) in the 0-5 cm soil depth

Months (M)	Land use (L)				Mean
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine	
April, 2018	110.82	96.72	95.58	94.14	99.32
May, 2018	112.38	97.54	97.06	93.66	100.16
June, 2018	114.64	99.50	98.76	92.96	101.47
July, 2018	116.96	100.80	99.14	94.48	102.85
August, 2018	111.18	99.12	99.28	94.80	101.10
September, 2018	106.84	98.24	96.18	95.66	99.23
October, 2018	104.78	97.90	95.42	95.18	98.32
November, 2018	101.58	97.26	94.32	95.42	97.15
December, 2018	99.28	98.24	92.38	94.98	96.22
January, 2019	96.18	95.84	90.26	93.86	94.04
February, 2019	93.66	94.16	89.50	93.22	92.64
March, 2019	93.04	92.54	88.38	92.94	91.73
Mean	105.11	97.32	94.69	94.28	
CD_{0.05}					
M	1.74				
L	1.00				
M×L	3.47				

The initial values of ammonical-N content in the 5-10 cm depth were 91.6, 82.1, 81.3 and 91.6 mg kg⁻¹ for forest, grassland, scrubland and unburnt chir pine, respectively (Table 3.1). The analysis of data on ammonical-N after fire, for the 5-10 cm depth, presented in Table 4.4 shows that ammonical-N in the soils varied significantly with land uses as well as with advancing time after fire. It varied from 90.66 mg kg⁻¹ in March, 2019 to 100.38 mg kg⁻¹ in July, 2018. In the forest land use, the results were significant and followed a similar trend with maximum ammonical-N content of 113.34 mg kg⁻¹ in July, 2018, which decreased continuously to 91.12 mg kg⁻¹ in March, 2019. In grassland and scrubland soil, the maximum

ammonical-N content was found to be in July, 2018 with values of 98.90 mg kg⁻¹ and 98.14 mg kg⁻¹, respectively and minimum ammonical-N content was to 90.92 mg kg⁻¹ and 87.58 mg kg⁻¹, respectively. When the different land uses were compared, it was observed that maximum ammonical-N content was in forest land use (102.90 mg kg⁻¹), which was significantly higher as compared to other land uses. The data on interaction effect between months and land use (M×L) presented in the table reveals a significant effect, with maximum ammonical-N (113.34 mg kg⁻¹) under forest land use in the month of July, 2018 which was statistically at par with June, 2018 (111.44 mg kg⁻¹) and August, 2018 (110.40 mg kg⁻¹) for the same land use and minimum was 87.58 mg kg⁻¹ for scrubland in the month of March, 2019.

Table 4.4: Ammonical-N content (mg kg⁻¹) in the 5-10 cm soil depth

Months (M)	Land use (L)				Mean
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine	
April, 2018	106.10	94.12	93.40	92.96	96.65
May, 2018	108.88	96.82	95.84	90.06	97.90
June, 2018	111.44	97.78	96.98	89.64	98.96
July, 2018	113.34	98.90	98.14	91.12	100.38
August, 2018	110.40	96.52	96.12	92.49	98.88
September, 2018	105.98	96.08	95.78	92.92	97.69
October, 2018	101.58	95.08	94.44	92.52	95.91
November, 2018	99.94	94.98	92.64	93.42	95.25
December, 2018	98.24	94.02	91.44	92.22	93.98
January, 2019	95.42	93.32	90.08	94.28	93.28
February, 2019	92.38	91.80	88.74	94.80	91.93
March, 2019	91.12	90.92	87.58	93.02	90.66
Mean	102.90	95.03	93.43	92.46	
CD_{0.05}					
M	1.60				
L	0.92				
M×L	3.19				

A cursory glance at the data in Table 4.5 indicates that there is a significant variation in the ammonical-N content of soils with land uses as well as months after the fire. The data shows that it varied from 87.72 mg kg⁻¹ in March, 2019 to 98.85 mg kg⁻¹ in July, 2018. In forest land use, the results were significant and followed a similar trend with maximum ammonical-N of 108.88 mg kg⁻¹ in July, 2018 and then it decreased to 90.08 mg kg⁻¹ in March, 2019. When different land uses were compared, it was observed that maximum ammonical-N content was in the forest land use (100.09 mg kg⁻¹) which was significantly

higher as compared to other three land uses. The interaction M×L shows that the maximum ammonical-N content (108.88 mg kg⁻¹) was under forest land use in the month of July, 2018 and minimum (84.58 mg kg⁻¹) was under scrubland in the month of March, 2019. The result shows that immediately after fire, the ammonical-N content in all the land uses increased for the first few months and thereafter reduced and was found minimum after one year. The initial values prior to the fire were 89.6, 81.5, 80.7 and 89.6 mg kg⁻¹ for forest, grassland, scrubland and unburnt chir pine, respectively (Table 3.1), its content increased with the onset of fire.

Table 4.5: Ammonical - N content (mg kg⁻¹) in the 10-15 cm soil depth

Months (M)	Land uses (L)				Mean
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine	
April, 2018	105.06	93.52	92.38	91.92	95.72
May, 2018	106.80	95.06	94.98	92.49	97.33
June, 2018	107.04	96.70	95.08	90.08	97.23
July, 2018	108.88	97.78	96.52	92.22	98.85
August, 2018	105.98	94.44	93.42	92.64	96.62
September, 2018	101.58	93.42	92.38	93.32	95.18
October, 2018	99.28	91.92	90.92	92.16	93.57
November, 2018	96.18	89.14	88.38	91.80	91.38
December, 2018	95.42	88.74	87.58	93.32	91.27
January, 2019	93.02	86.78	85.98	94.80	90.15
February, 2019	91.80	86.18	84.76	93.60	89.09
March, 2019	90.08	85.16	84.58	91.04	87.72
Mean	100.09	91.57	90.58	92.45	
CD_{0.05}					
M	1.61				
L	0.93				
M×L	3.23				

The data in Table 4.3 to 4.5 also shows that the ammonical-N content was higher in the surface depth (0-5 cm) and it decreased with the increase in soil depth irrespective of the land uses. The results obtained in the present study are in agreement with the findings of Nardoto and Bustamante (2003) who reported that there was a significant increase of inorganic-N due to an increase in NH₄⁺-N concentration immediately after the fire. However, in the following months after the fire, NH₄⁺-N concentration decreased in comparison to pre-fire levels. Similar results were also reported by Stock and Lewis (1986) and Turner *et al.* (2007) who concluded that ammonium-N concentration peaked immediately after fire and then shows declining trend. Prieto- Fernandez *et al.* (1993) compared the surface (0-5 cm)

and sub-surface (5-10 cm) layers from the burnt soil with the corresponding layers from the same unburnt soil and reported that total inorganic N, which was mainly in the form of NH_4^+ -N, increased after the burning in both the layers. The fire considerably increased the NH_4^+ -N content in the burnt soil, the difference with respect to the unburnt soil being greater in the surface layer (19-fold) than in the deeper one (15- fold); consequently the NH_4^+ -N content in the burnt surface layer was significantly higher than that in the subsurface one. The results are also in agreement with the findings of Wan et al. (2001) who reported that the soil NH_4^+ pool increased approximately two fold immediately after fire and then gradually declined to the pre-fire level after one year. Knoepp and Swank (1993) have suggested that the observed increase in soil NH_4^+ after fire may have resulted from two processes: (1) volatilization of organic N from the soil surface and its condensation after downward movement into cooler soil layer and (2) increases in N mineralization caused by altered micro-climate, soil temperature and pH value as well as increased microbial activities.

4.2.2 Nitrate nitrogen (mg kg^{-1})

The initial nitrate-N content values of 51.2, 49.3, 50.2 and 51.2 mg kg^{-1} in forest, grassland, scrubland and unburnt chir pine, respectively, presented in Table 3.1 shows that with the introduction of the fire the nitrate-N content in the soil increased significantly after the fire.

An examination of the data presented in Table 4.6 reveals that the nitrate-N content varied significantly. The nitrate-N content varied from 51.28 mg kg^{-1} in April, 2018 to 67.43 mg kg^{-1} in March, 2019. Thus, although the nitrate-N content remains almost same as that of pre-fire level in the first few months, but afterwards it shows an increasing trend. In the forest land use, the results were significant and followed the same trend, with maximum nitrate-N content of 77.22 mg kg^{-1} in the month of March, 2019 and minimum was 51.92 mg kg^{-1} in the month of May, 2018. In grassland and scrubland, the minimum nitrate-N content was 51.92 mg kg^{-1} and 51.32 mg kg^{-1} in the month of April, 2018, respectively, which increased continuously to 71.30 mg kg^{-1} and 70.50 mg kg^{-1} in the month of March, 2019, respectively. When different land uses were compared, it was observed that maximum nitrate-N was in the forest land use (65.64 mg kg^{-1}), which was significantly higher as compared to the other land uses whereas, nitrate-N content of grassland and scrubland were found to be statistically at par. The interaction M×L shows that maximum nitrate-N content of 77.22 mg kg^{-1} was under

forest land use in the month of March, 2019 which was statistically at par with the nitrate-N content in the same land use in the month of February, 2019 (75.54 mg kg⁻¹). The minimum nitrate-N of 47.30 mg kg⁻¹ in the month of July, 2018 was for unburnt chir pine site. The results shows that after fire, the nitrate-N content was almost similar to that of pre-fire level for first few months and thereafter increased and was found maximum at the end of the study period (March, 2019).

Table 4.6 : Nitrate-N content (mg kg⁻¹) in the 0-5 cm soil depth

Months (M)	Land uses (L)				Mean
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine	
April, 2018	52.00	51.92	51.32	49.86	51.28
May, 2018	51.92	52.74	52.58	48.88	51.53
June, 2018	54.92	53.76	52.86	49.54	52.77
July, 2018	59.42	58.96	58.40	47.30	56.02
August, 2018	64.54	62.54	61.78	48.96	59.46
September, 2018	66.54	63.96	64.42	50.80	61.43
October, 2018	71.10	67.08	65.78	51.44	63.85
November, 2018	73.20	70.00	69.24	52.04	66.12
December, 2018	69.68	63.86	63.74	49.54	61.71
January, 2019	71.54	64.94	64.08	49.46	62.51
February, 2019	75.54	67.76	66.98	48.84	64.78
March, 2019	77.22	71.30	70.50	50.68	67.43
Mean	65.64	62.40	61.81	49.78	
CD_{0.05}					
M	1.71				
L	0.99				
M×L	3.41				

The data depicted in Table 4.7 reflects that there is a significant variation in nitrate-N content at 5-10 cm soil depth, with land uses as well as with increasing months post-fire. The maximum nitrate-N content of 73.77 mg kg⁻¹ was in March, 2019 which was statistically significant as compared to all the other months. In forest soil, the minimum nitrate-N concentration was 57.10 mg kg⁻¹ in the month of April, 2018 and maximum was found to be 85.18 mg kg⁻¹ in the month of March, 2019. Similar trend was observed for grassland and scrubland soil. When different land uses were compared, the maximum nitrate-N content was in the forest land use (70.93 mg kg⁻¹) which was statistically higher than all the other land uses, whereas grassland and scrubland soils were found to be statistically at par. The interaction M×L shows that the maximum nitrate-N content of 85.18 mg kg⁻¹ was under forest land use in the month of March, 2019 and the minimum of 50.84 mg kg⁻¹ was under

unburnt chir pine in the month of February, 2019. The results shows that even at 5-10 cm depth post- fire, the nitrate-N content increased significantly after few months of fire and thereafter, shows increasing trend and was found maximum after one year. The initial values of nitrate-N for the four land uses were 54.6, 53.8, 53.1 and 54.6 mg kg⁻¹, respectively (Table 3.1) and when these values were compared to the values after twelve months of fire, it is seen that the nitrate-N content in all the land uses after fire increased, but not in the unburnt chir pine site. Also, the maximum nitrate-N was observed in the 5-10 cm soil depth for all the land uses.

Table 4.7 : Nitrate-N content (mg kg⁻¹) in the 5-10 cm soil depth

Months (M)	Land uses (L)				Mean
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine	
April, 2018	57.10	55.50	54.14	51.66	54.60
May, 2018	59.46	57.78	57.52	51.50	56.57
June, 2018	61.26	59.60	59.46	51.90	58.05
July, 2018	64.22	61.12	61.46	50.92	59.43
August, 2018	67.32	63.70	63.46	51.98	61.62
September, 2018	69.92	65.92	64.78	52.62	63.31
October, 2018	73.66	70.34	71.12	53.42	67.14
November, 2018	76.08	71.02	71.90	52.12	67.78
December, 2018	76.20	65.92	66.90	51.36	65.10
January, 2019	78.68	73.62	72.46	51.34	69.03
February, 2019	82.12	77.10	78.82	50.84	72.22
March, 2019	85.18	77.96	78.22	53.72	73.77
Mean	70.93	66.63	66.69	51.95	
CD_{0.05}					
M	1.40				
L	0.81				
M×L	2.80				

An inquisition of the data in Table 4.8 clearly indicates that nitrate-N content in the 10-15 cm soil depth varied in a similar way as for other soil depths. The nitrate-N content varied from 52.07 mg kg⁻¹ in May, 2018 to 72.72 mg kg⁻¹ in March, 2019. The value for February, 2019 (71.37 mg kg⁻¹) was found to be statistically at par with the maximum value. In forest soil, the minimum nitrate-N concentration was 53.06 mg kg⁻¹ in the month of May, 2018 and maximum was found to be 84.58 mg kg⁻¹ in the month of March, 2019. When different land uses were compared, it was observed that maximum nitrate-N of 69.26 mg kg⁻¹ was found in forest landuse, which was statistically significant as compared to other land uses. Whereas, grassland and scrubland were found to be statistically at par. The interaction

M×L indicates that the maximum nitrate-N content of 84.58 mg kg⁻¹ was under forest land use in the month of March, 2019 which was at par with its value in February, 2019 (81.72 mg kg⁻¹), and the minimum of 50.50 mg kg⁻¹ was under unburnt chir pine in the month of May, 2019. These values were also found to be higher in the fire sites to their respective pre-fire values i.e. 51.8, 51.6, 50.7 and 51.8 mg kg⁻¹ for forest, grassland, scrubland and unburnt chir pine, respectively (Table 3.1).

Table 4.8 : Nitrate-N content (mg kg⁻¹) in the 10-15 cm soil depth

Months (M)	Land uses (L)				Mean
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine	
April, 2018	53.38	52.70	52.50	50.86	52.36
May, 2018	53.06	52.58	52.12	50.50	52.07
June, 2018	59.66	57.40	56.06	51.90	56.26
July, 2018	62.62	60.32	60.86	52.12	58.98
August, 2018	66.52	62.90	63.46	52.58	61.37
September, 2018	68.92	64.92	64.18	51.62	62.41
October, 2018	72.26	69.54	70.32	52.42	66.14
November, 2018	74.88	70.02	70.70	51.52	66.78
December, 2018	74.80	64.52	65.80	50.76	63.97
January, 2019	78.68	72.82	71.46	50.74	68.43
February, 2019	81.72	76.10	77.82	49.84	71.37
March, 2019	84.58	76.36	77.42	52.52	72.72
Mean	69.26	65.02	65.23	51.45	
C.D_{0.05}					
M	1.51				
L	0.87				
M×L	3.02				

These results are in confirmation with those of Wan et al. (2001) who reported that the fire-induced increase in the soil NO₃⁻ pool was small immediately after fire, reached a maximum of approximately threefold of the pre-fire level within 0.5-1 year after fire, and then declined. Stock and Lewis (1986) reported that nitrate-N concentration increased after fire which lasted for nine months. Christensen (1973) had also reported high-NO₃⁻-N concentrations following a chaparral fire which he attributed to the destruction of nitrification inhibitors by fire. Prieto-Fernandez *et al.* (1993) confirmed that the deeper layer of the burnt soil showed a significantly higher NO₃⁻-N content, which was 6-fold the value in the corresponding unburnt layer and almost 3-fold that in the burnt surface layer. The increase of NO₃⁻-N in the subsurface layer of the burnt soil can be attributed to the fact that the temperature reached in this layer was not high enough to inactivate the nitrifying microbial

population or to the incomplete thermal decomposition of nitrates under conditions of oxygen deficiency (Raison, 1979). This increase could also be due to leaching of nitrates from the surface layer on the occasion of the rain which took place between the fire and the sampling.

4.3 MINERALIZATION BEHAVIOUR IN SOIL AFTER FIRE

Based on the ammonical and nitrate-N contents, the net ammonification and nitrification were calculated by simple empirical formula of deducting the values of corresponding months from their respective initial values.

4.3.1 Ammonification (mg kg^{-1})

An examination of the data presented in Table 4.9 reveals that the ammonification rate increased in the first four months after fire and thereafter, shows a declining trend. In forest land use, the ammonification rate was maximum (23.18 mg kg^{-1}) in the month of July, 2018 and the minimum (-0.74 mg kg^{-1}) was in the month of March, 2019.

Table 4.9: Ammonification (mg kg^{-1}) in the 0-5 cm soil depth

Months (M)	Land uses (L)			
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine
April, 2018	17.04	13.15	12.98	0.36
May, 2018	18.60	13.97	14.46	-0.12
June, 2018	20.86	15.93	16.16	-0.82
July, 2018	23.18	17.23	16.54	0.70
August, 2018	17.40	15.55	16.68	1.02
September, 2018	13.06	14.67	13.58	1.88
October, 2018	11.00	14.33	12.82	1.40
November, 2018	7.80	13.69	11.72	1.64
December, 2018	5.50	14.67	9.78	1.20
January, 2019	2.40	12.27	7.66	0.08
February, 2019	-0.12	10.59	6.90	-0.56
March, 2019	-0.74	8.97	5.78	-0.84

In grassland and scrubland soil, the maximum ammonification rate was 17.23 mg kg^{-1} and 16.68 mg kg^{-1} in the month of July, 2018 and August, 2018, respectively, whereas, the minimum ammonification rate was 8.97 mg kg^{-1} and 5.78 mg kg^{-1} in the month of March, 2019, respectively. It is also observed that the ammonification rate was less as compared to its initial values after ten months of fire in the forest ecosystem. Also, when the values of the land uses are observed, it is seen that the ammonification was higher in the forest followed by

grasslands and scrublands, whereas, the rate of ammonification did not show any appreciable change in the unburnt chir pine forest.

Table 4.10: Ammonification (mg kg⁻¹) in the 5-10 cm soil depth

Months (M)	Land uses (L)			
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine
April, 2018	14.50	11.98	12.10	1.36
May, 2018	17.28	14.68	14.54	-1.54
June, 2018	19.84	15.64	15.68	-1.96
July, 2018	21.74	16.76	16.84	-0.48
August, 2018	18.80	14.38	14.82	0.89
September, 2018	14.38	13.94	14.48	1.32
October, 2018	9.98	12.94	13.14	0.92
November, 2018	8.34	12.84	11.34	1.82
December, 2018	6.64	11.88	10.14	0.62
January, 2019	3.82	11.18	8.78	2.68
February, 2019	0.78	9.66	7.44	3.20
March, 2019	-0.48	8.78	6.28	1.42

A perusal of the data presented in Table 4.10 reflects rate of ammonification in the soil at 5-10 cm soil depth after fire. As in the case of surface layers, in forest land use, maximum and minimum ammonification rates of 21.74 mg kg⁻¹ and -0.48 mg kg⁻¹ was found in the month of July, 2018 and March, 2019, respectively. In grassland, the maximum ammonification rate was 16.76 mg kg⁻¹ in the month of July, 2018 and minimum ammonification rate was 8.78 mg kg⁻¹ in the month of March, 2019. For scrublands, the maximum and minimum values of 16.84 and 6.28 mg kg⁻¹ were for July, 2018 and March, 2019, respectively

A glance of data in Table 4.11 reveals that the rate of ammonification increased in the first few months after fire, and thereafter shows a declining trend in all the land uses, even in the 10-15 cm soil depth. In forest land use, the ammonification rate was maximum (19.28 mg kg⁻¹) in the month of July, 2018 and minimum (0.48 mg kg⁻¹) was in the month of March, 2019. In grassland and scrubland soil, the maximum ammonification rate was 16.26 mg kg⁻¹ and 15.82 mg kg⁻¹ in the month of July, 2018, respectively whereas, the minimum ammonification rate of 3.64 mg kg⁻¹ and 3.88 mg kg⁻¹ were observed in the month of March, 2019, respectively. It is also seen that the ammonification rate in the surface layer was higher as compared to the sub- surface layers.

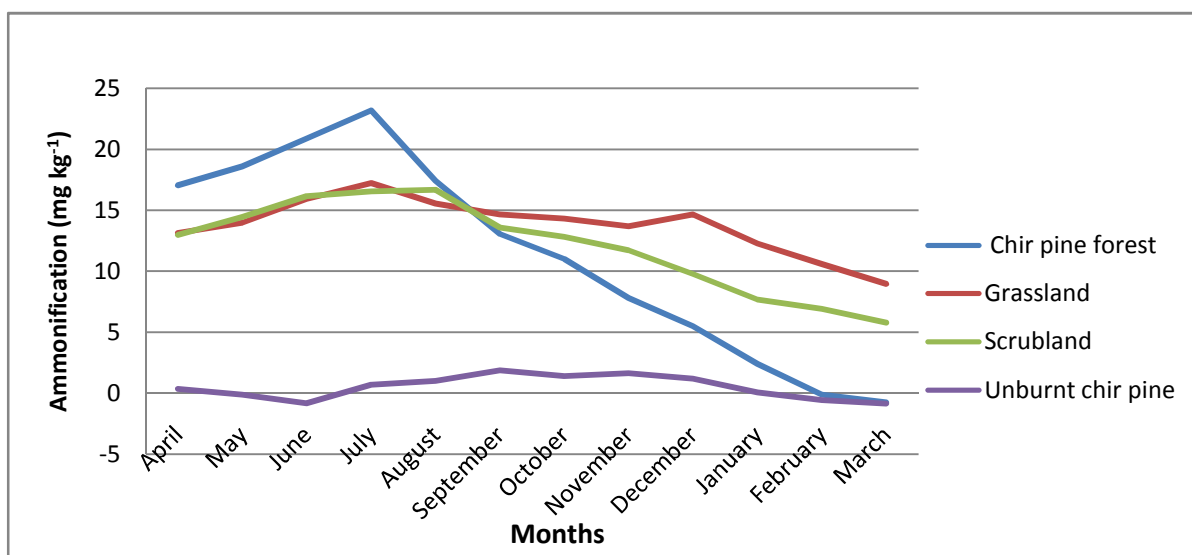


Fig. 4.1 Ammonification (mg kg⁻¹) in the 0-5 cm soil depth

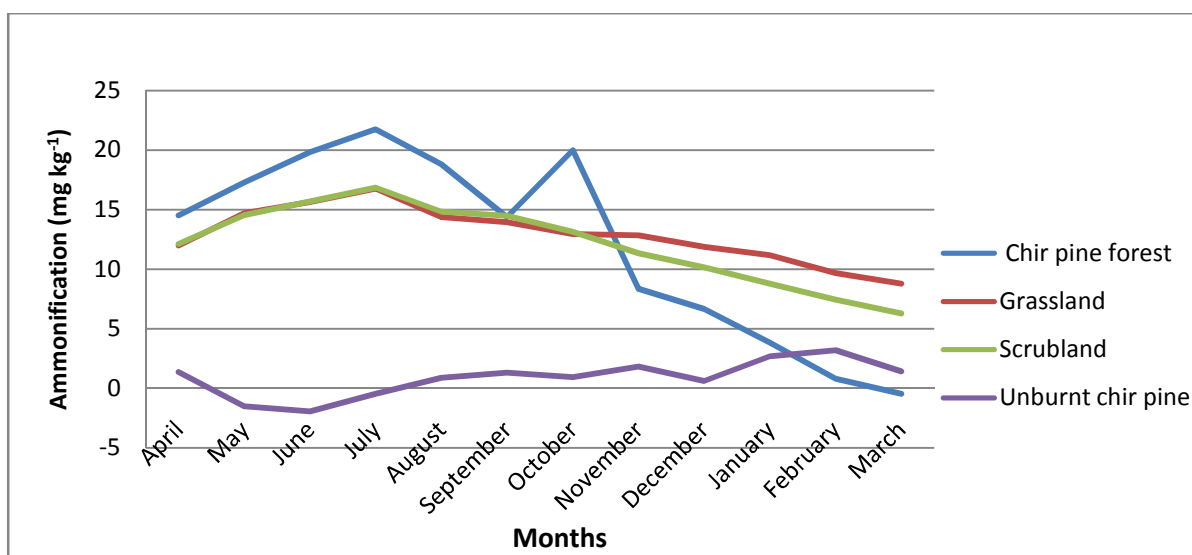


Fig. 4.2 Ammonification (mg kg⁻¹) in the 5-10 cm soil depth

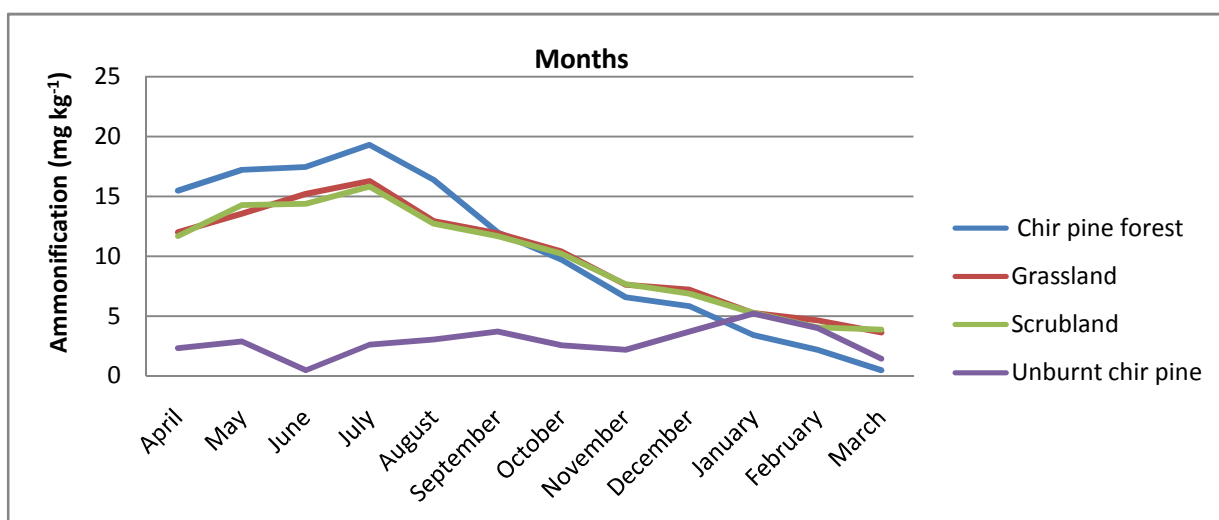


Fig. 4.3 Ammonification (mg kg⁻¹) in the 10-15 cm soil depth

Table 4.11: Ammonification (mg kg^{-1}) in the 10-15 cm soil depth

Months (M)	Land uses (L)			
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine
April, 2018	15.46	12.00	11.68	2.32
May, 2018	17.20	13.54	14.28	2.89
June, 2018	17.44	15.18	14.38	0.48
July, 2018	19.28	16.26	15.82	2.62
August, 2018	16.38	12.92	12.72	3.04
September, 2018	11.98	11.90	11.68	3.72
October, 2018	9.68	10.40	10.22	2.56
November, 2018	6.58	7.62	7.68	2.20
December, 2018	5.82	7.22	6.88	3.72
January, 2019	3.42	5.26	5.28	5.20
February, 2019	2.20	4.66	4.06	4.00
March, 2019	0.48	3.64	3.88	1.44

Wilbur and Christensen (1983); and Adams and Attiwill (1986) have also reported higher ammonification rate after the fire which ultimately tend to reach the pre-fire levels after one year. The results are also in line with the findings of Covington *et al.* (1991) and Monleon *et al.* (1997)

4.3.2 Nitrification (mg kg^{-1})

An examination of the data presented in Table 4.12 reveals that the nitrification was low initially, after fire for a few months, and thereafter it shows an increasing trend. In forest land use, the nitrification was maximum (26.02 mg kg^{-1}) in the month of March, 2019 and minimum (0.72 mg kg^{-1}) in the month of May, 2018. In grassland and scrubland soil, the maximum nitrification was 22.00 mg kg^{-1} and 20.30 mg kg^{-1} , respectively in the month of March, 2019 and minimum nitrification was 2.62 mg kg^{-1} and 1.12 mg kg^{-1} , respectively in the month of April, 2018. Among all the land uses, the maximum nitrification of 26.02 mg kg^{-1} was found under forest land use and minimum of -3.90 mg kg^{-1} was found under unburnt chire pine. Higher values of nitrification were observed in forest land use after the fire. It was also seen that the nitrification rate increased after July i.e. after the onset of rainy season.

Table 4.12 : Nitrification (mg kg⁻¹) in the 0-5 cm soil depth

Months (M)	Land uses (L)			
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine
April, 2018	0.80	2.62	1.12	-1.34
May, 2018	0.72	3.44	2.38	-2.32
June, 2018	3.72	4.46	2.66	-1.66
July, 2018	8.22	9.66	8.20	-3.90
August, 2018	13.34	13.24	11.58	-2.24
September, 2018	15.34	14.66	14.22	-0.40
October, 2018	19.90	17.78	15.58	0.24
November, 2018	22.00	20.70	19.04	0.84
December, 2018	18.48	14.56	13.54	-1.66
January, 2019	20.34	15.64	13.88	-1.74
February, 2019	24.34	18.46	16.78	-2.36
March, 2019	26.02	22.00	20.30	-0.52

A perusal of the data presented in Table 4.13 reflects the rate of nitrification in the soil at 5-10 cm depth after fire. In forest land use, maximum and minimum nitrification of 30.58 mg kg⁻¹ and 2.5 mg kg⁻¹ were found in the month of March, 2019 and April, 2018, respectively. Similar trend was observed for grassland soil. In scrubland, the maximum nitrification of 25.72 mg kg⁻¹ was found in the month of February, 2019 and minimum nitrification of 1.04 mg kg⁻¹ was found in the month of April, 2018. The pattern for the nitrification rates were similar to that of the surface layer, but was a little higher than the surface depth for fire subjected land uses.

Table 4.13 : Nitrification (mg kg⁻¹) in the 5-10 cm soil depth

Months (M)	Land uses (L)			
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine
April, 2018	2.5	1.70	1.04	-2.94
May, 2018	4.86	3.98	4.42	-3.10
June, 2018	6.66	5.80	6.36	-2.70
July, 2018	9.62	7.32	8.36	-3.68
August, 2018	12.72	9.90	10.36	-2.62
September, 2018	15.32	12.12	11.68	-1.98
October, 2018	19.06	16.54	18.02	-1.18
November, 2018	21.48	17.22	18.80	-2.48
December, 2018	21.60	12.12	13.80	-3.24
January, 2019	24.08	19.82	19.36	-3.26
February, 2019	27.52	23.30	25.72	-3.76
March, 2019	30.58	24.16	25.12	-0.88

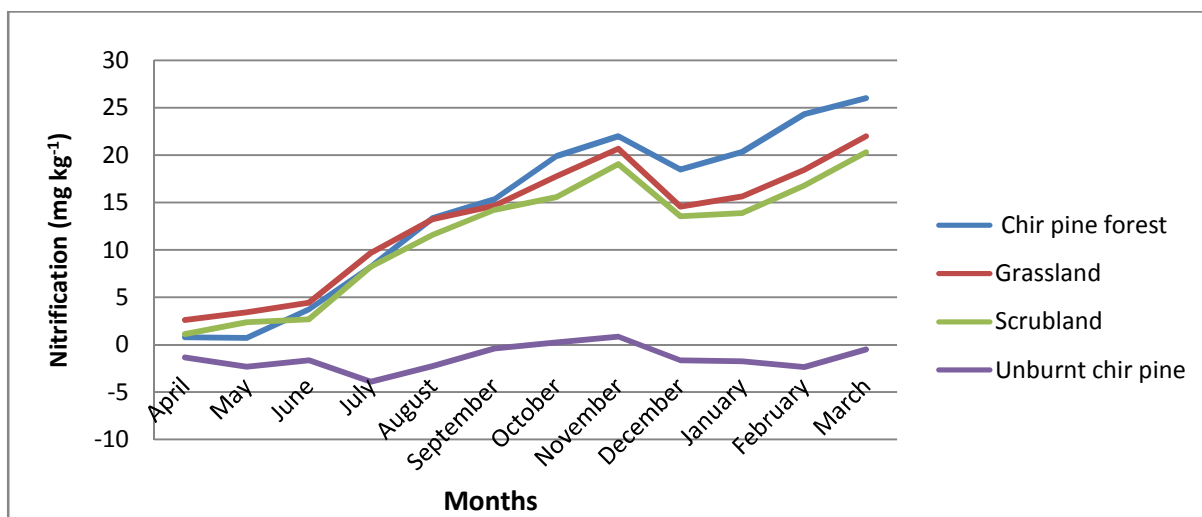


Fig. 4.4 Nitrification (mg kg^{-1}) in the 0-5 cm soil depth

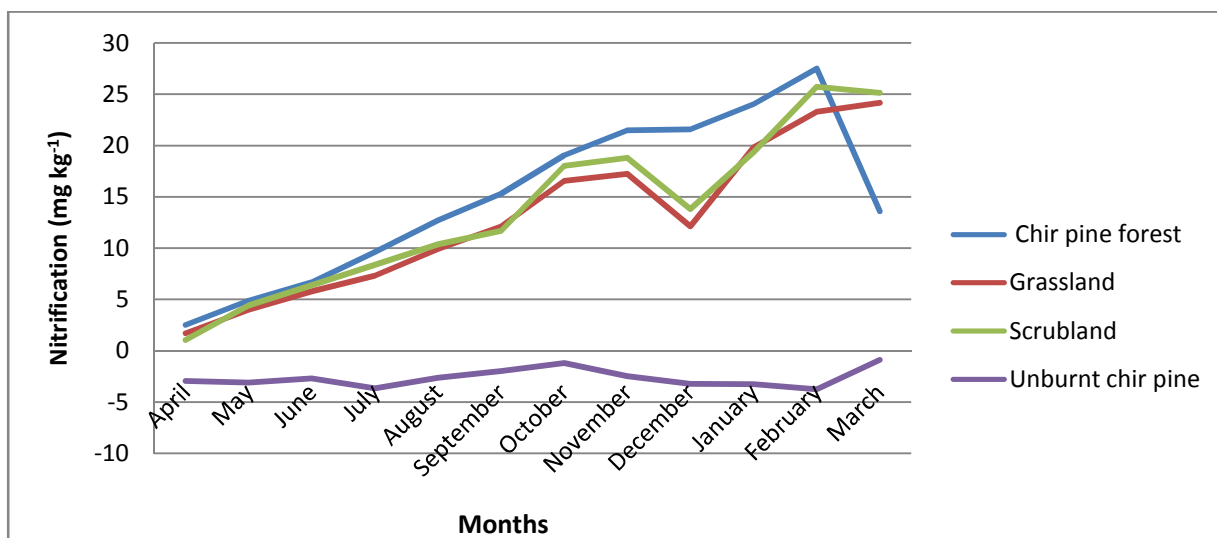


Fig. 4.5 Nitrification (mg kg^{-1}) in the 5-10 cm soil depth

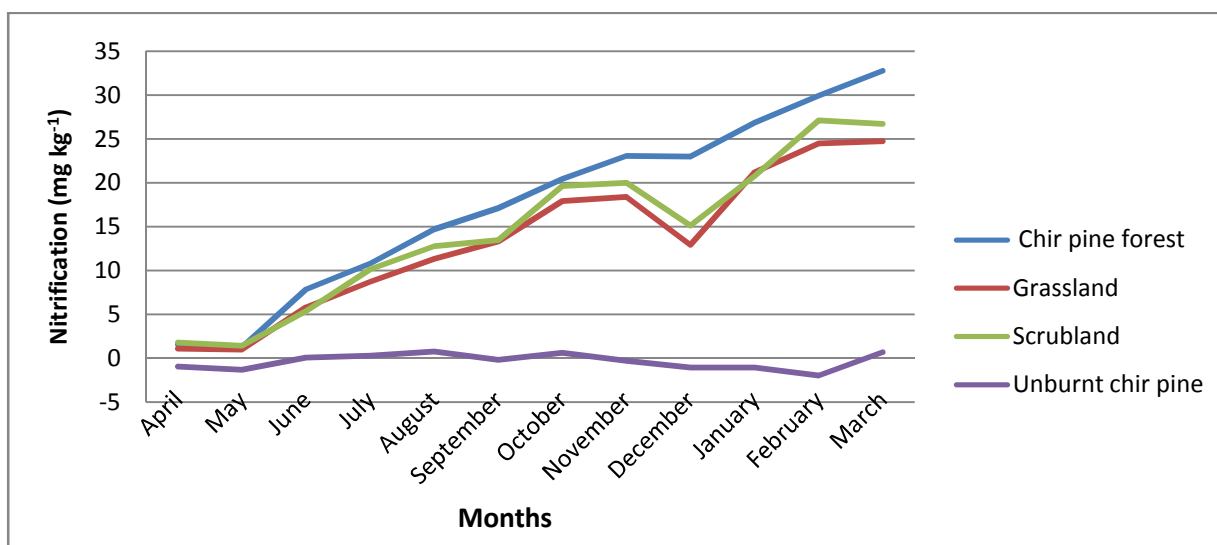


Fig. 4.6 Nitrification (mg kg^{-1}) in the 10-15 cm soil depth

An inquisition of data in Table 4.14 also indicates a similar pattern in the 10-15 cm soil depth with the nitrification initially low after fire for a few months and thereafter, shows an increasing trend. In forest land use, the nitrification was maximum (32.78 mg kg^{-1}) in the month of March, 2019 and was minimum (1.26 mg kg^{-1}) in the month of May, 2018. In grassland and scrubland soil, the maximum nitrification was 24.76 mg kg^{-1} and 27.12 mg kg^{-1} were in the month of March and February, 2019, respectively and minimum nitrification was 0.98 mg kg^{-1} and 1.42 mg kg^{-1} in the month of May, 2018, respectively. Among all the land uses, the maximum nitrification of 32.78 mg kg^{-1} was found under forest land use and minimum of -1.96 mg kg^{-1} was found under unburnt chir pine.

Table 4.14 : Nitrification (mg kg^{-1}) in the 10-15 cm soil depth

Months (M)	Land uses (L)			
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine
April, 2018	1.58	1.10	1.80	-0.94
May, 2018	1.26	0.98	1.42	-1.30
June, 2018	7.86	5.80	5.36	0.10
July, 2018	10.82	8.72	10.16	0.32
August, 2018	14.72	11.3	12.76	0.78
September, 2018	17.12	13.32	13.48	-0.18
October, 2018	20.46	17.94	19.62	0.62
November, 2018	23.08	18.42	20.00	-0.28
December, 2018	23.00	12.92	15.10	-1.04
January, 2019	26.88	21.22	20.76	-1.06
February, 2019	29.92	24.50	27.12	-1.96
March, 2019	32.78	24.76	26.72	0.72

4.3.3 Net mineralization (mg kg^{-1})

The net mineralization i.e. the conversion of organic N to inorganic N was worked at by the simple addition of the total ammonification and nitrification for pre-fire month and then subtracting from its corresponding values in March, 2019.

The data enumerated in Table 4.15 shows that in forest land use, the initial ammonical plus nitrate-N content was 145.0, 146.2 and 141.4 mg kg^{-1} for 0-5, 5-10 and 10-15 cm depths, respectively. The final ammonical plus nitrate-N content was 170.3 for 0-5 cm, 176.3 for 5-10 cm and 174.7 mg kg^{-1} for 10-15 cm depths. In grassland, the initial ammonical plus nitrate-N for 0-5 cm, 5-10 cm and 10-15 cm were 132.9, 135.9 and 133.1 mg kg^{-1} , respectively. The final ammonical plus nitrate-N for grassland was 163.8, 168.9 and 161.5 mg kg^{-1} for 0-5, 5-10 and 10-15 cm depths, respectively. In scrubland the values were 132.8, and 158.9 mg kg^{-1} , respectively for 0-5 cm, 131.4 and 165.8 mg kg^{-1} , respectively for 5-10

cm and 131.4 and 162.0 mg kg⁻¹, respectively for 10-15 cm depth. In unburnt chir pine site the initial values for 0-5 cm, 5-10 cm and 10-15 cm were 145.0, 146.2 and 141.4 mg kg⁻¹, respectively, whereas, the final values were 143.6, 146.7 and 143.6 mg kg⁻¹ for 0-5, 5-10 and 10-15 cm depths, respectively. In forest land use the net mineralization was 25.3 mg kg⁻¹ for 0-5 cm, 30.1 mg kg⁻¹ for 5-10 cm and 33.3 mg kg⁻¹ for 10-15 cm depths with a net mineralization rate of 0.06, 0.08 and 0.09 mg N kg⁻¹ per day. In grass land, the net mineralization for 0-5 cm, 5-10 cm and 10-15 cm depths was 30.9, 33.0 and 28.4 mg kg⁻¹, respectively. In scrubland, net mineralization for 0-5 cm was 26.1 mg kg⁻¹, for 5-10 cm it was 31.4 mg kg⁻¹ and for 10-15 cm it was 30.6 mg kg⁻¹. In unburnt chir pine site, net immobilisation was observed with a value of -1.4 mg kg⁻¹ for 0-5 cm depth, whereas, the net mineralization for 5-10 and 10-15 cm depth was 0.5 and 2.2 mg kg⁻¹, respectively, with a net mineralization rate of 0.001 and 0.006 mg N kg⁻¹ per day for the respective depths.

Table 4.15: Ammonical + Nitrate nitrogen and net mineralization (mg kg⁻¹) under different land uses

Property	Ammonical + Nitrate Nitrogen (mg kg ⁻¹)		Net Mineralization (mg kg ⁻¹)
Land use and Depth	Initial	Final	
Chir pine forest			
0-5 cm	145.0	170.3	25.3 (0.06)
5-10 cm	146.2	176.3	30.1 (0.08)
10-15 cm	141.4	174.7	33.3 (0.09)
Grassland			
0-5 cm	132.9	163.8	30.9 (0.09)
5-10 cm	135.9	168.9	33.0 (0.09)
10-15 cm	133.1	161.5	28.4 (0.08)
Scrubland			
0-5 cm	132.8	158.9	26.1 (0.01)
5-10 cm	131.4	165.8	31.4 (0.08)
10-15 cm	131.4	162.0	30.6 (0.08)
Unburnt chir pine			
0-5 cm	145.0	143.6	-1.4 (-0.004)
5-10 cm	146.2	146.7	0.5 (0.001)
10-15 cm	141.4	143.6	2.2 (0.006)

Figures in parentheses indicate net mineralization rate on daily basis

The rates of net N mineralization were high and variable due to deposition of organic matter and non-uniformity of burnings. Net N mineralization is related to total N in soil, and quality of organic matter (Hossain *et al.*, 1995). Also, the contribution of NH₄⁺-N towards net mineralization was greater than the nitrate-N (Nardoto and Bustamante, 2003). The negative values indicate immobilization. The results are in line with findings of Singh *et al.* (1989).

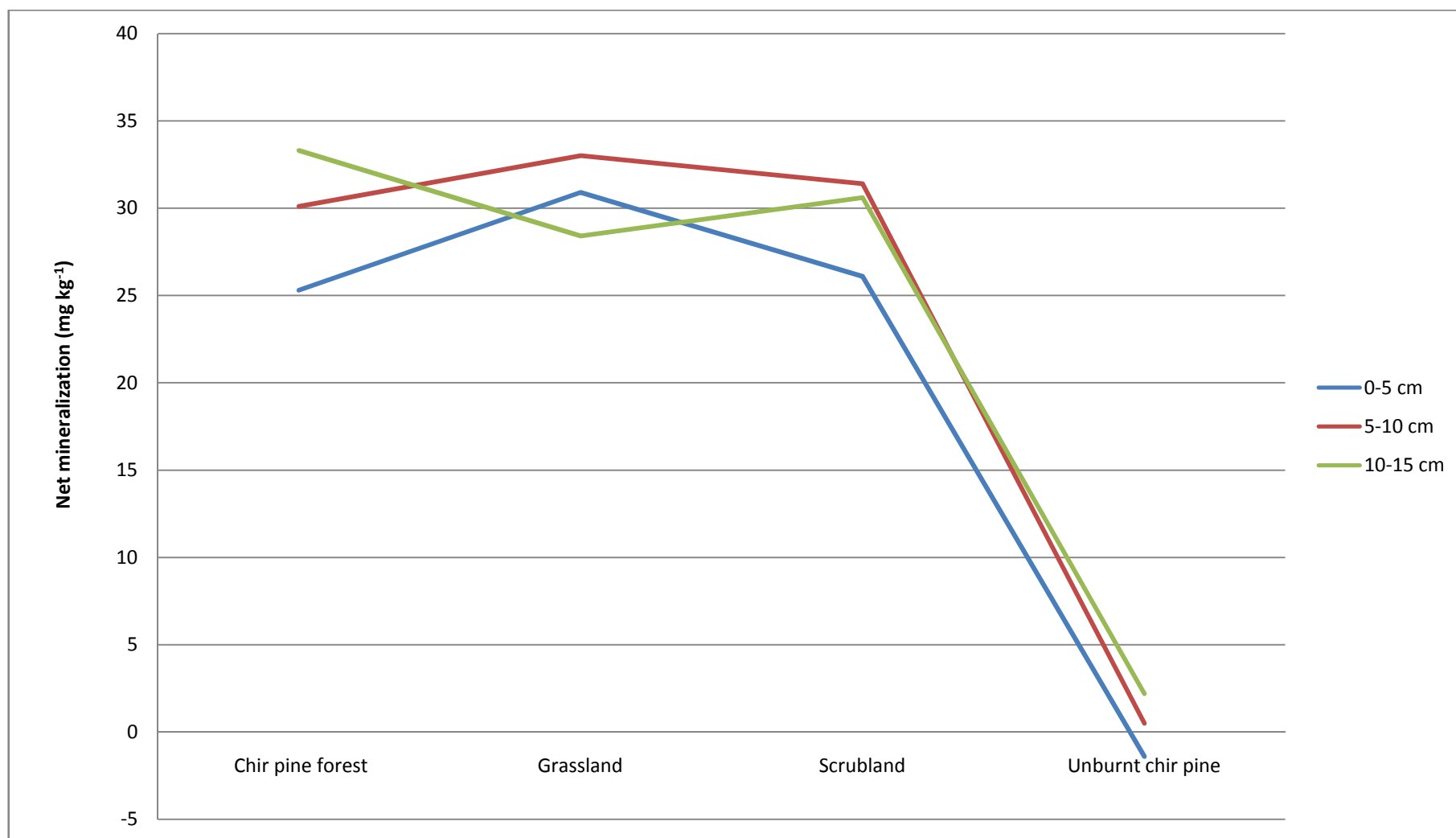


Fig 4.7 Net mineralization (mg kg⁻¹) in the soils under different land uses at different depths

4.4 CHANGES IN SOIL CARBON AFTER FIRE

4.4.1 Organic carbon (per cent)

The data on organic carbon in the soil (0-5 cm depth) at monthly intervals after the fire is presented in Table 4.16. The results indicated that organic carbon content after fire in all the land uses decreased as compared to pre-fire level and then subsequently increased upto twelve months after the fire. The pre-fire level of organic carbon in forest, grassland, scrubland and unburnt chir pine soils were 1.23, 1.38, 1.31 and 1.23 per cent, respectively (Table 4.1). The maximum organic carbon after fire of 1.29 per cent was in the month of March, 2019 which was statistically at par with December, 2018, January and February, 2019. In burnt forest, organic carbon was found maximum in the month of March, 2019 with an average of 1.21 per cent and minimum was in the month of April, 2018 with an average of 1.08 per cent. Similar trend was observed for grassland as well as for scrubland. When different land uses were compared, the maximum percentage of organic carbon was found under grassland with an average of 1.30 per cent which was found at par with unburnt chir pine (1.29 per cent) and minimum was found under forest land use with an average of 1.16 per cent. The data on interaction between months and land use (M×L) was found to be non-significant. It is also observed that in comparison to the initial levels, the organic carbon content decreased markedly immediately after the fire but in a period of twelve months it reached almost to the pre-fire level.

Table 4.16: Organic carbon (per cent) in the 0-5 cm soil depth

Months (M)	Land uses (L)				Mean
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine	
April, 2018	1.08	1.22	1.14	1.24	1.17
May, 2018	1.10	1.23	1.15	1.25	1.19
June, 2018	1.11	1.25	1.17	1.27	1.20
July, 2018	1.14	1.27	1.18	1.28	1.22
August, 2018	1.15	1.29	1.20	1.28	1.23
September, 2018	1.16	1.30	1.21	1.28	1.24
October, 2018	1.17	1.30	1.22	1.29	1.25
November, 2018	1.18	1.32	1.24	1.30	1.26
December, 2018	1.19	1.33	1.25	1.30	1.27
January, 2019	1.19	1.34	1.26	1.30	1.27
February, 2019	1.20	1.35	1.27	1.31	1.28
March, 2019	1.21	1.36	1.29	1.31	1.29
Mean	1.16	1.30	1.22	1.29	
CD _{0.05}					
M	0.02				
L	0.01				
M×L	NS				

An inquisition of data in Table 4.17 clearly indicates that the organic carbon percentage content in the 5-10 cm depth also varied significantly with land uses as well as with advancing months after fire. The organic carbon varied from 1.10 per cent in the month of April, 2018 to 1.19 per cent in the month of March, 2019. In forest, the maximum organic carbon was found in the month of March, 2019 with an average of 1.15 per cent and minimum was found in the month of April, 2018 and July, 2018 with an average of 1.07 per cent. Similar trend was observed for other land uses as well. When different land uses were compared, the maximum organic carbon was found under unburnt chir pine site with an average of 1.21 and minimum was found under forest land use with an average of 1.11 per cent. The data on interaction between months and land use (M×L) was found to be non-significant.

Table 4.17: Organic carbon (per cent) in the 5-10 cm soil depth

Months (M)	Land uses (L)				Mean
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine	
April, 2018	1.07	1.08	1.07	1.16	1.10
May, 2018	1.08	1.09	1.08	1.17	1.11
June, 2018	1.08	1.10	1.07	1.18	1.11
July, 2018	1.07	1.11	1.09	1.20	1.12
August, 2018	1.10	1.12	1.10	1.21	1.13
September, 2018	1.10	1.14	1.12	1.22	1.14
October, 2018	1.11	1.15	1.14	1.22	1.16
November, 2018	1.12	1.16	1.16	1.23	1.17
December, 2018	1.13	1.17	1.16	1.23	1.17
January, 2019	1.13	1.17	1.17	1.24	1.18
February, 2019	1.14	1.18	1.17	1.25	1.19
March, 2019	1.15	1.19	1.18	1.25	1.19
Mean	1.11	1.14	1.13	1.21	
CD_{0.05}					
M	0.02				
L	0.01				
M×L	NS				

The data depicted in Table 4.18 reflects that the organic carbon content varied from 1.07 per cent in the month of April, 2018 to 1.18 in the month of March, 2019. In forest land use, the maximum organic carbon was found in the month of March, 2019 with an average of 1.13 per cent and minimum was found in the month of April, 2018 with an average of 1.03 per cent. In grassland and scrubland, the maximum organic carbon was found in the month of March, 2019 with an average of 1.17 per cent in both the land uses and minimum was found

in the month of April, 2018 with an average of 1.07 per cent and 1.05 per cent respectively. When different land uses were compared, the maximum organic carbon percentage was found under unburnt chir pine site with an average of 1.19 per cent which was significantly higher than all other land uses, whereas, minimum was found under forest land use with an average of 1.10 per cent. The data on interaction between months and land use (M×L) was found to be non-significant. The data presented in Table 4.16 to Table 4.18 also reveals that organic carbon percentage decreased with increase in soil depth.

Table 4.18 : Organic carbon (per cent) in the 10-15 cm soil depth

Months (M)	Land uses (L)				Mean
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine	
April, 2018	1.03	1.07	1.05	1.13	1.07
May, 2018	1.04	1.08	1.06	1.14	1.08
June, 2018	1.06	1.09	1.07	1.16	1.10
July, 2018	1.07	1.10	1.09	1.17	1.11
August, 2018	1.09	1.11	1.10	1.18	1.12
September, 2018	1.10	1.13	1.12	1.18	1.13
October, 2018	1.11	1.14	1.13	1.20	1.15
November, 2018	1.11	1.15	1.15	1.20	1.15
December, 2018	1.12	1.15	1.16	1.21	1.16
January, 2019	1.12	1.16	1.16	1.21	1.16
February, 2019	1.13	1.16	1.16	1.23	1.17
March, 2019	1.13	1.17	1.17	1.23	1.18
Mean	1.10	1.13	1.12	1.19	
CD_{0.05}					
M	0.02				
L	0.01				
M×L	NS				

Similar results were reported by Johnson and Curtis (2001) who found that low-temperature fires i.e. prescribed fire may cause little initial loss in mineral soil C as compared to unburnt site, but may result in later gains due to the incorporation of unburned residues (including charcoal). Salgado *et al.* (1995) also reported loss of organic matter during the fire, provoking a low concentration of fuel after the fire, with consequent increase in the ignition temperature. The results are also in agreement with the findings of Fernandez *et al.* (1997) who reported that the organic C content had decreased considerably after the fire. The decrease was approximately 50%, however, C losses were even higher in the surface layer, which was much more morphologically altered as compared to sub-surface layers.

4.4.2 Microbial biomass carbon ($\mu\text{g g}^{-1}$ soil)

The microbial biomass carbon in the soils at 0-5 cm depth (Table 4.19) varied significantly with land uses as well as with advancing months post-fire. The microbial biomass carbon varied from $147.86 \mu\text{g g}^{-1}$ of soil in April, 2018 to $162.86 \mu\text{g g}^{-1}$ of soil in March, 2019. The maximum value was significantly higher as compared to other months. Thus, the microbial biomass carbon decreased after fire and then subsequently increased upto twelve months after the fire. In the forest land use, the results were significant and followed a similar trend with minimum microbial biomass carbon of $155.50 \mu\text{g g}^{-1}$ of soil in April, 2018 which increased continuously to $172.92 \mu\text{g g}^{-1}$ of soil in March, 2019. When the different land uses were compared, it was observed that the maximum microbial biomass carbon was found in the unburnt chir pine site ($181.04 \mu\text{g g}^{-1}$ of soil) which was significantly higher as compared to the other three land uses. The data on interaction between months and land use (M×L) was found to be non-significant.

Table 4.19: Microbial biomass carbon ($\mu\text{g g}^{-1}$ soil) in the 0-5 cm soil depth

Months (M)	Land uses (L)				Mean
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine	
April, 2018	155.50	131.28	130.42	174.22	147.86
May, 2018	157.92	134.18	132.76	175.96	150.21
June, 2018	160.16	135.54	134.84	177.04	151.90
July, 2018	163.00	137.01	135.46	178.06	153.38
August, 2018	165.20	139.66	137.86	179.94	155.67
September, 2018	166.63	140.71	138.64	181.84	156.96
October, 2018	166.11	141.26	140.66	182.06	157.52
November, 2018	167.06	142.06	141.05	183.62	158.45
December, 2018	167.71	143.06	142.27	183.98	159.26
January, 2019	168.78	143.22	143.26	184.52	159.95
February, 2019	170.07	145.04	143.65	184.84	160.90
March, 2019	172.92	147.08	145.06	186.38	162.86
Mean	165.09	140.01	138.83	181.04	
CD _{0.05}					
M	1.85				
L	1.07				
M×L	NS				

The data depicted in Table 4.20 reflects that there is a significant variation in microbial biomass carbon at 5-10 cm soil depth. The maximum microbial biomass carbon of $166.73 \mu\text{g g}^{-1}$ of soil was found in March, 2019 which was significantly higher as compared to other months. In forest soil, the minimum microbial biomass carbon of $158.39 \mu\text{g g}^{-1}$ of

soil was found in the month of April, 2018 and maximum of 175.69 $\mu\text{g g}^{-1}$ of soil was found in the month of March, 2019. Similar trend was observed for grassland and scrubland soil. When different land uses were compared, the maximum microbial biomass carbon was found in the unburnt chir pine site (183.45 $\mu\text{g g}^{-1}$ of soil) and minimum was found in the scrubland (141.13 $\mu\text{g g}^{-1}$ of soil). The data on interaction between months and land use (M×L) was found to be non-significant.

Table 4.20: Microbial biomass carbon ($\mu\text{g g}^{-1}$ soil) in the 5-10 cm soil depth

Months (M)	Land uses (L)				Mean
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine	
April, 2018	158.39	134.40	133.98	176.59	150.84
May, 2018	160.63	135.65	134.28	177.18	151.94
June, 2018	163.07	139.86	136.58	179.52	154.76
July, 2018	165.19	140.47	138.99	180.70	156.34
August, 2018	166.68	141.38	139.69	182.13	157.47
September, 2018	168.63	143.58	140.55	183.43	159.05
October, 2018	169.30	144.04	141.76	184.09	159.80
November, 2018	170.40	145.46	143.44	185.42	161.18
December, 2018	170.19	147.17	144.72	186.06	162.04
January, 2019	171.91	147.68	144.58	186.56	162.68
February, 2019	173.09	149.12	146.26	188.30	164.20
March, 2019	175.69	151.19	148.66	191.39	166.73
Mean	167.77	143.33	141.13	183.45	
CD_{0.05}					
M	1.78				
L	1.03				
M×L	NS				

An inquisition of the data in Table 4.21 clearly indicates that microbial biomass carbon in the 10-15 cm depth also varied significantly. The microbial biomass carbon varied from 146.94 $\mu\text{g g}^{-1}$ of soil in April, 2018 to 159.55 $\mu\text{g g}^{-1}$ of soil in March, 2019, and the maximum value was found to be statistically at par with the value in the month of February, 2019 (157.87 $\mu\text{g g}^{-1}$ of soil). In forest soil, the minimum microbial biomass carbon of 154.18 $\mu\text{g g}^{-1}$ of soil was found in the month of April, 2018 and maximum was found to be 169.80 $\mu\text{g g}^{-1}$ of soil in the month of March, 2019. When different land uses were compared, it was observed that significantly maximum microbial biomass carbon of 178.47 $\mu\text{g g}^{-1}$ of soil was found in the unburnt chir pine site, whereas, minimum of 137.32 $\mu\text{g g}^{-1}$ of soil was found in the grassland soil. The microbial biomass carbon seems to be directly related to the distribution of organic carbon in soils.

Table 4.21: Microbial biomass carbon ($\mu\text{g g}^{-1}$ soil) in the 10-15 cm soil depth

Months (M)	Land uses (L)				Mean
	Chir pine forest	Grassland	Scrubland	Unburnt chir pine	
April, 2018	154.18	131.34	129.73	172.52	146.94
May, 2018	155.58	132.42	133.10	173.98	148.77
June, 2018	157.72	134.40	133.52	175.42	150.27
July, 2018	159.06	136.20	134.36	176.04	151.42
August, 2018	161.20	137.17	136.20	177.06	152.91
September, 2018	162.56	138.21	138.57	178.64	154.50
October, 2018	163.40	139.22	139.36	179.24	155.31
November, 2018	164.37	138.64	139.44	179.33	155.45
December, 2018	165.12	139.06	140.28	180.98	156.36
January, 2019	165.80	139.43	140.86	181.94	157.01
February, 2019	167.40	139.68	141.44	182.94	157.87
March, 2019	169.80	142.04	142.76	183.58	159.55
Mean	162.18	137.32	137.47	178.47	
CD_{0.05}					
M	1.91				
L	1.10				
M×L	NS				

The results are in confirmation with the findings of Choromanska and DeLuca (2002) who reported that initially, the fire exposed soil had lower basal respiration rate and lower concentrations of microbial biomass carbon than the soils not exposed to fire due to C substrate loss during fire and fire-induced microbial mortality. Fires initially decreased soil biomass C by soil heating, then a quick microbial recovery has been reported in some wet forest soils (Di'az-Ravina *et al.*, 1996; Prieto-Fernandez *et al.*, 1998; Vazquez *et al.*, 1993). Fritze *et al.* (1994) working with forest soils, found that burning caused a 50% decrease in the total microbial biomass.

4.5 SOIL PROPERTIES AT THE END OF THE EXPERIMENT UNDER DIFFERENT LAND USES

4.5.1 Soil physico-chemical properties

i. Soil texture

The texture of the soil after the fire season (12 months) remained the same and was worked out to be gravelly silty clay loam.

ii. Bulk density (Mg m^{-3})

The results presented in Table 4.22 on soil physico-chemical properties under different land uses one year after the fire shows that the bulk density of surface (0-5 cm)

depth in forest soil increased to 1.12 Mg m^{-3} and to 1.15 Mg m^{-3} for 10-15 cm depth. In the grassland soil, the bulk density values for 0-5 cm, 5-10 cm and 10-15 cm depths were 1.15, 1.17 and 1.17 Mg m^{-3} , respectively. Similarly, for scrublands the final values were 1.14, 1.15 and 1.17 Mg m^{-3} , respectively. In the unburnt chir pine site, the bulk density values were 1.11, 1.13 and 1.14 Mg m^{-3} , for the respective depths showing an increasing trend with soil depth. Thus, the increase in bulk density after fire is insignificant being less than 1 per cent over the initial values.

Table 4.22: Soil physico-chemical properties under different land uses one year after the fire

Property Land use and Depth	Bulk density (g cm⁻³)	pH (1:2)	EC (dS m⁻¹)	Organic carbon (%)
Chir pine forest				
0-5 cm	1.12 (0.90)	5.94 (0.51)	0.48 (2.14)	1.21 (-1.63)
5-10 cm	1.13 (0.89)	5.92 (0.34)	0.47 (0.0)	1.15 (-0.86)
10-15 cm	1.15 (0.88)	5.91 (0.0)	0.46 (0.0)	1.13 (-0.88)
Grassland				
0-5 cm	1.15 (0.88)	6.07 (0.50)	0.53 (1.92)	1.36 (-1.45)
5-10 cm	1.17 (1.74)	6.04 (0.17)	0.52 (0.0)	1.19 (-2.46)
10-15 cm	1.17 (0.86)	6.06 (0.17)	0.52 (0.0)	1.17 (-1.68)
Scrubland				
0-5 cm	1.14 (0.89)	6.15 (0.33)	0.55 (1.84)	1.29 (-0.76)
5-10 cm	1.15 (0.88)	6.12 (0.16)	0.54 (0.0)	1.18 (-3.28)
10-15 cm	1.17 (0.86)	6.13 (0.16)	0.53 (-1.85)	1.17 (-0.85)
Unburnt chir pine				
0-5 cm	1.11 (0.0)	5.91 (0.0)	0.47 (0.0)	1.35 (9.76)
5-10 cm	1.13 (0.89)	5.90 (0.0)	0.47 (0.0)	1.25 (7.76)
10-15 cm	1.14 (0.0)	5.89 (0.0)	0.47 (-2.12)	1.23 (11.40)

Figure in parenthesis indicate per cent change

iii. Soil pH

The data on soil pH under different land uses one year after the fire is enumerated in Table 4.22 shows that the soil pH increased slightly after the fire. In forest soil, pH values were 5.94, 5.92 and 5.91 for 0-5 cm, 5-10 cm and 10-15 cm depth, respectively. In the grassland site, the soil pH values for 0-5 cm was 6.07, for 5-10 cm, it was 6.04 and for 10-15 cm depth, it was 6.06 respectively. Similarly, for scrublands the initial soil pH values for 0-5 cm, 5-10 cm and 10-15 cm depth were 6.15, 6.12 and 6.13, respectively. In the unburnt chir pine site, the soil pH values were 5.91, 5.90 and 5.89 for the respective depths. The per cent change in the pH of burnt land uses varied from 0.16 to 0.51 per cent, which is very less.

iv. Electrical conductivity (dS m^{-1})

An examination of the data presented in Table 4.22 depicts that the EC of 0-5 cm depth in forest soil after fire was 0.48 dS m^{-1} and it was found to increase to 0.47 dS m^{-1} for 5-10 cm depth after fire and 0.46 dS m^{-1} for 10-15 cm depth. The EC values for 0-5 cm, 5-10 cm and 10-15 cm depths were 0.53, 0.52 and 0.52 dS m^{-1} respectively in the grassland site. Similarly, for scrublands the EC values after fire were 0.55, 0.54 and 0.53 dS m^{-1} , respectively. No major changes in the salt content of soils after fire was observed.

v. Organic carbon (per cent)

A perusal of the data on soil organic carbon presented in Table 4.22 reveals that in forest soil, organic carbon was found to be 1.21 per cent for 0-5 cm depth and 1.15 per cent and 1.13 per cent for 5-10 cm and 10-15 cm depth, respectively. The data shows that organic carbon was found low one year after fire as compared to pre-fire level. Similarly, for grassland the values were 1.36, 1.19 and 1.17 per cent for the respective depths. In the scrubland, the values were 1.29, 1.18 and 1.17 per cent for 0-5 cm, 5-10 cm and 10-15 cm depth respectively. In the unburnt chir pine site, the organic carbon values after fire were 1.35, 1.25 and 1.23 per cent for 0-5 cm, 5-10 cm and 10-15 cm depth respectively. The organic carbon values declined post-fire being -0.76 to -3.28 per cent of the initial values.

4.5.2 Available nutrient content in soil

i. Nitrogen (kg ha^{-1})

The data pertaining to available nitrogen in soil one year after fire under different land uses is enumerated in Table 4.23 and it shows that available nitrogen values were 304.6, 291.2 and 274.3 kg ha^{-1} for 0-5 cm, 5-10 cm and 10-15 cm depth, respectively in the forest soil. It also shows that available nitrogen increased slightly one year after fire in all the land uses. In the grassland, the available N values for 0-5 cm, 5-10 cm and 10-15 cm depth were 304.8, 294.6 and 287.8 kg ha^{-1} , respectively. The available nitrogen values one year after fire were 306.2, 291.3 and 280.2 kg ha^{-1} for the respective depths in the scrubland. The nitrogen content increased by 0.70 to 3.17 per cent in burnt sites, and 0.47 to 1.17 per cent in unburnt chir pine.

ii. Phosphorus (kg ha^{-1})

Appraisal of data in Table 4.23 reflects that available phosphorus one year after fire of surface depth (0-5 cm) in forest soil was 25.8 kg ha^{-1} and it was found to decrease to 25.7 kg ha^{-1} for 10-15 cm depth. In the grassland soil, the available phosphorus values for 0-5, 5-10 and 10-15 cm depths were 27.9, 31.2 and 27.1 kg ha^{-1} , respectively. The available phosphorus values for 0-5, 5-10 and 10-15 cm soil depths were 25.8, 27.3 and 25.4 kg ha^{-1} , respectively

in scrubland and 24.1, 26.9 and 25.3 kg ha⁻¹ for the respective depths in the unburnt chir pine site one year after fire. No major changes in the phosphorus content was observed after one year post-fire.

Table 4.23: Available N, P and K contents under different land uses one year after the fire

Property Land use and Depth	N (kg ha⁻¹)	P (kg ha⁻¹)	K (kg ha⁻¹)
Chir pine forest			
0-5 cm	304.6 (2.84)	25.8 (2.38)	275.3 (0.95)
5-10 cm	291.2 (1.01)	27.2 (3.03)	278.6 (1.27)
10-15 cm	274.3 (0.70)	25.7 (5.76)	274.1 (0.26)
Grassland			
0-5 cm	304.8 (0.73)	27.9 (2.57)	323.3 (1.19)
5-10 cm	294.6 (1.10)	31.2 (5.76)	327.4 (1.84)
10-15 cm	287.8 (1.70)	27.1 (1.50)	325.8 (1.75)
Scrubland			
0-5 cm	306.2 (2.61)	25.8 (1.57)	320.1 (0.88)
5-10 cm	291.3 (1.39)	27.3 (0.0)	323.6 (1.06)
10-15 cm	280.2 (3.17)	25.4 (3.25)	321.2 (0.78)
Unburnt chir pine			
0-5 cm	306.9 (1.69)	24.1 (0.84)	273.3 (0.59)
5-10 cm	297.8 (0.47)	26.9 (3.07)	276.2 (0.33)
10-15 cm	289.4 (1.83)	25.3 (1.61)	275.7 (0.77)

Figure in paranthesis indicate per cent change

iii. Potassium (kg ha⁻¹)

A scrutiny of the data presented in Table 4.23 reveals that available potassium one year after fire in forest soils were 275.3, 278.6 and 274.1 kg ha⁻¹ for 0-5, 5-10 and 10-15 cm depths, respectively. In the grassland soils, the available potassium in surface depth was 323.3 kg ha⁻¹ and it was found 325.8 kg ha⁻¹ for 10-15 cm depth. In the scrubland, available potassium values for 0-5, 5-10 and 10-15 cm were 320.1, 323.6 and 321.2 kg ha⁻¹, respectively. In the unburnt chir pine site, the available potassium values were 273.3, 276.2 and 275.7 kg ha⁻¹ for the respective depths one year after the fire, thus no major changes in potassium content of soils was observed after the fire.

In general, the fire did not have any significant effect on soil properties. The observations are in line with the reports of Nardoto and Bustamante (2003). The very low values of per cent change in the soil properties (Table 4.22 and 4.23) indicate that the soil properties were influenced by the forest fires initially, but with the passage of time the soil returns to the pre-fire conditions.

Chapter - 5

SUMMARY AND CONCLUSION

The investigation entitled **“Effect of fire on mineralization of soil organic matter”** was carried out at five sites located at Dr. Y.S. Parmar University of Horticulture and Forestry Nauni, Solan, Himachal Pradesh, during the year 2018 – 2019, with the following objectives:

- To determine the effects of forest fires on net nitrogen mineralization and carbon
- To evaluate the effects of forest fires on the microbial biomass and their activity

Four land uses (viz. Chir pine forests, grasslands, scrubland and unburnt chir pine) were selected for the purpose. Initial soil samples were collected from all the land uses. Thereafter, a controlled fire was made in all the land uses in March, 2018. Soil samples (0 to 5 cm, 5 - 10 cm and 10-15 cm depths) from a plot size of 50m× 50m for each land use at each site, were collected at monthly intervals upto March, 2019. The studies were conducted on the Net mineralization (Ammonification + Nitrification) after the fire and changes in soil organic carbon and microbial biomass carbon. The results obtained in the present study are summarized below:

- The soils under different land uses had bulk density varying from 1.11- 1.16 Mg m⁻³. The soils of grassland and scrubland had higher bulk density than the soils of chir pine forest land use. The soil texture class was gravelly silty clay loam.
- The pH varied from 5.89-6.13 and EC values were normal. The organic carbon in the soils ranged from 1.14- 1.38 per cent. The available N,P and K varied from 170.2-180.2, 23.9-29.5 and 271.7-321.5 kg ha⁻¹, respectively.
- The ammonical- N content of 0-5 cm depth in chir pine forest soils was higher (105.11 mg kg⁻¹) and the minimum was in unburnt chir pine (94.28 mg kg⁻¹). The ammonical- N was found to increase significantly after the fire in March, the content increased upto August and thereafter, shows a decline.
- The ammonical-N content in 5-10 cm and 10-15 cm depths shows a decreasing trend but the variation within months followed the same trend as was observed in the surface (0-5 cm) layer. Also the unburnt chir pine had lower ammonical-N than the scrublands and grasslands.

- The nitrate-N of 0-5 cm depth was maximum (65.64 mg kg⁻¹) in the chir pine forest land use as compared to the minimum value in unburnt chir pine (49.78 mg kg⁻¹). The nitrate-N content varied with land use in the order Chir pine forest > Grassland > Scrubland > Unburnt chir pine, indicating a positive effect of fire on the nitrification.
- The nitrate-N was found to be maximum after 12 months i.e. in March, 2019 (67.43 mg kg⁻¹). In the initial months, its content was found low due to ammonification upto August, and thereafter, the nitrification was found to increase. The nitrate-N in the 5-10 cm and 10-15 cm depths followed the same trend with respect to land uses and duration (months).
- The net ammonification in chir pine forest land use for 0-5 cm depth was maximum (23.18 mg kg⁻¹) in the month of July and minimum (-0.74 mg kg⁻¹) was after one year i.e. March 2019. In the grasslands, it was maximum in July (17.23 mg kg⁻¹) and minimum in March (8.97 mg kg⁻¹). For scrubland maximum (16.68 mg kg⁻¹) was in August as compared to a minimum of (5.78 mg kg⁻¹) in March. In the non- fire site, however, the ammonification was very low, with the maximum (1.88 mg kg⁻¹) in September and a minimum (0.84 mg kg⁻¹) in March. The ammonification rate in 5-10 cm and 10-15 cm depths followed the similar trend.
- The nitrification rate in 0-5 cm depth in chir pine forest ecosystem was maximum (26.02 mg kg⁻¹) in March, 2019 after fire and minimum in May, 2018 (0.72 mg kg⁻¹). A positive impact of chir pine forest fire was seen on nitrification and the trend was same in grasslands and scrublands. In the unburnt chir pine the maximum nitrification of (0.84 mg kg⁻¹) was in November, 2018. The same trend was observed for 5-10 cm and 10-15 cm depths, although, the values of nitrification decreased with the increase in soil depths.
- The net mineralization in the 0-5 cm depth after the chir pine forest fire was maximum (30.9 mg kg⁻¹) with a mineralization rate of 0.09 mg N kg⁻¹ per day in the grassland, while the value for chir pine forest, scrubland and unburnt chir pine for 0-5 cm depth was 25.3, 26.1 and -1.4 mg kg⁻¹, respectively. The results for the lower (5-10 and 10-15 cm) soil depths followed the same distribution pattern. The net mineralization rate in forest (10-15 cm depth) and grassland (0-5 and 5-10 cm depth) was almost equal i.e. 0.09 mg N kg⁻¹ per day, thus indicating the role of forest fire as well as quality of organic matter in determining mineralization.
- On an average, organic carbon in the 0-5 cm depth in grasslands was maximum (1.30 per cent) followed by unburnt chir pine (1.29 per cent), scrubland (1.22 per cent) and

chir pine forest (1.16 per cent). The organic carbon content was found to increase with duration (months) after the fire in all the land uses. The 5-10 cm and 10-15 cm depths registered decreasing values, although the trend was similar.

- The soil microbial biomass carbon also varied from 155.5-172.9 ($\mu\text{g g}^{-1}$ soil) in forest, 131.28-147.08 ($\mu\text{g g}^{-1}$ soil) in grassland, 130.42-145.06 ($\mu\text{g g}^{-1}$ soil) in scrubland and 174.22-186.38 ($\mu\text{g g}^{-1}$ soil) in unburnt chir pine site. The distribution pattern with respect to months after fire and land uses, followed the similar trend as that of soil organic carbon.
- The available nutrient content was found to increase marginally after one year with the burnt sites showing an increase of 0.70 to 3.17 per cent while the N content in unburnt soils increased in the range of 0.47 to 1.83 per cent. The per cent increase in available P content ranged from 0.0 to 5.76 per cent in the unburnt sites while it was 0.84 to 3.07 per cent in the unburnt sites. Similarly, the K content increased between 0.26 to 1.84 per cent in burnt sites and 0.33 to 0.77 per cent in unburnt sites.

CONCLUSION:

1. From the present investigation it is concluded that in the chir pine forests, after the incidence of fire, the ammonical nitrogen content increased upto four months and thereafter decreased, whereas, the nitrate nitrogen content remained initially less but after a few months started increasing. The process of mineralization, which is a sum of ammonification and nitrification was maximum in sub-surface layers of burnt forest and in the surface layers of grassland. The effect of chir pine forest fires on mineralization was observed to be maximum in the surface layer and it decreased with the increase in soil depth.
2. The organic carbon content was maximum in grasslands, and after the fire in all the land uses, the organic carbon content decreased in the first four months and subsequently increased upto twelve months after the fire. The soil microbial biomass carbon followed the similar pattern and was found to vary with the distribution of organic carbon in the soil. The organic carbon and microbial activity decreased with the increase in soil depth.

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APPENDIX-I

Agro-meteorological data of the study area (March 2018 – March 2019)

Month	Temperature (°C)			Rainfall (mm)	Evaporation (mm)
	Max.	Min.	Mean		
March, 2018	24.3	8.8	16.55	17.4	59.5
April, 2018	27.1	12.6	19.85	39.6	81.5
May, 2018	30.7	16.1	23.4	54.9	120.6
June, 2018	29.7	18.9	24.3	190.0	114.8
July, 2018	26.7	20.2	23.45	340.2	65.1
August, 2018	27.6	20.0	23.8	216.6	76.3
September, 2018	26.5	16.9	21.7	224.3	55.4
October, 2018	25.1	9.1	17.1	2.6	56.2
November, 2018	21.7	6.5	14.1	24.8	45.5
December, 2018	18.1	1.6	9.85	21.6	37.7
January, 2019	15.7	2.0	8.85	73.0	31.7
February, 2019	16.3	4.4	10.35	103.1	24.5
March, 2019	20.3	6.6	13.45	54.6	36.8

Source: Meteorological Observatory of the Department of Environmental Science, Dr. YS Parmar University of Horticulture and Forestry, Nauni, Solan (HP) - 173 230

APPENDIX- II

Analysis of Variance Table (ANOVA)

1. Analysis of variance for ammonical-N (0-5 cm depth)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	4	85.103		33.108
Months	11	2,813.668	255.788	196.281
Land uses	3	4,549.361	1,516.454	8.295
Months $\times$ Land uses	33	2,114.902	64.088	
Error	189	1,452.477	7.726	
Total	239	11,015.511		

2. Analysis of variance for ammonical-N (5-10 cm depth)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	4	114.793		
Months	11	2,008.368	182.579	27.978
Land uses	3	4,067.982	1,355.994	207.789
Months $\times$ Land uses	33	2,215.853	67.147	10.289
Error	189	1,226.858	6.526	
Total	239	9,633.853		

3. Analysis of variance for ammonical-N (10-15 cm depth)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	4	77.086		
Months	11	2,964.654	269.514	40.343
Land uses	3	3,406.252	1,135.417	169.957
Months $\times$ Land uses	33	1,534.370	46.496	6.960
Error	189	1,255.959	6.681	
Total	239	9,238.320		

4. Analysis of variance for nitrate-N (0-5 cm depth)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	4	74.483		
Months	11	7,152.276	650.207	87.044
Land uses	3	8,713.068	2,904.356	388.811
Months $\times$ Land uses	33	2,261.364	68.526	9.174
Error	189	1,404.331	7.470	
Total	239	19,605.522		

5. Analysis of variance for nitrate-N (5-10 cm depth)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	4	659.774		
Months	11	8,390.039	762.731	151.629
Land uses	3	12,444.639	4,148.213	824.657
Months $\times$ Land uses	33	2,817.621	85.382	16.974
Error	189	945.683	5.030	
Total	239	25,257.756		

6. Analysis of variance for nitrate-N (10-15 cm depth)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	4	149.811		
Months	11	10,311.297	937.391	160.626
Land uses	3	10,876.977	3,625.659	621.273
Months $\times$ Land uses	33	3,737.867	113.269	19.409
Error	189	1,097.141	5.836	
Total	239	26,173.094		

7. Analysis of variance for organic carbon (0-5 cm depth)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	4	0.011		
Months	11	0.252	0.023	21.156
Land uses	3	0.388	0.129	119.219
Months $\times$ Land uses	33	0.019	0.001	0.521
Error	189	0.204	0.001	
Total	239	0.873		

8. Analysis of variance for organic carbon (5-10 cm depth)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	4	0.011		
Months	11	0.252	0.023	21.156
Land uses	3	0.388	0.129	119.219
Months $\times$ Land uses	33	0.019	0.001	0.521
Error	189	0.204	0.001	
Total	239	0.873		

9. Analysis of variance for organic carbon (10-15 cm depth)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	4	0.016		
Months	11	0.285	0.026	25.284
Land uses	3	0.284	0.095	92.242
Months × Land uses	33	0.012	0.000	0.358
Error	189	0.193	0.001	
Total	239	0.789		

10. Analysis of variance for microbial biomass carbon (0-5 cm depth)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	4	165.293		
Months	11	5,175.439	470.494	58.031
Land uses	3	74,365.872	24,788.624	3,057.422
Months × Land uses	33	61.330	1.858	0.229
Error	189	1,524.246	8.108	
Total	239	81,292.179		

11. Analysis of variance for microbial biomass carbon (5-10 cm depth)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	4	169.670		
Months	11	4,594.947	417.722	47.696
Land uses	3	75,596.728	25,198.909	2,877.259
Months × Land uses	33	77.842	2.359	0.269
Error	189	1,646.496	8.758	
Total	239	82,085.682		

12. Analysis of variance for microbial biomass carbon (10-15 cm depth)

Source of Variation	DF	Sum of Squares	Mean Squares	F-Calculated
Replication	4	63.708		
Months	11	3,268.704	297.155	31.884
Land uses	3	73,049.441	24,349.814	2,612.676
Months × Land uses	33	126.547	3.835	0.411
Error	189	1,752.136	9.320	
Total	239	78,260.537		

**Department of Soil Science and Water Management
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Title of thesis : **“Effect of fire on mineralization of soil organic matter”**
Name of the student : Sakshi Vishvamitera
Admission number : F-2017-46-M
Major Advisor : Dr. Uday Sharma
Major field : Soil Science
Minor field : Silviculture and Agroforestry
Degree Awarded : M.Sc (Ag.) Soil Science
Year of Award of degree : 2019
Number of Pages in thesis : 77+iv
Number of words in Abstract : 356

ABSTRACT

The investigation entitled **“Effect of fire on mineralization of soil organic matter”** was carried out at five sites located at Dr. Y.S. Parmar University of Horticulture and Forestry Nauni, Solan, Himachal Pradesh, during the year 2018-2019, with an aim to determine the effect of fire on nitrogen mineralization, organic carbon and microbial biomass carbon. The comparison of four land uses (viz. Forests, grasslands, scrubland and unburnt chir pine) was made with respect to the studied parameters. A controlled fire was made in all the land uses in March, 2018. Soil samples (0 to 5 cm, 5 - 10 cm and 10-15 cm depths) from a plot size of 50m × 50m for each land use at each site, were collected at monthly intervals upto March, 2019. The soils of the area had bulk density varying from 1.11- 1.16 Mg m⁻³ and pH varying from 5.89-6.13. The available N, P and K varied from 170.2-180.2, 23.9-29.5 and 271.7-321.5 kg ha⁻¹, respectively. The ammonical- N content of 0-5 cm depth in forest soils was higher (105.11 mg kg⁻¹) which increased upto August and thereafter declined. The content also decreased with depth. The nitrate-N of 0-5 cm depth was maximum (65.64 mg kg⁻¹) in the forest land use compared to the minimum in unburnt chir pine site (49.78 mg kg⁻¹). The nitrate-N content varied with land use in the order Forest > Grassland > Scrubland > Unburnt chir pine site. The net mineralization in the 0-5 cm depth was maximum (30.9 mg kg⁻¹) in forest land use. The maximum rate of mineralization (0.09 mg N kg⁻¹day⁻¹) was in sub-surface layers of forest and for surface layers of grassland, after the fire. Organic carbon was in the order: grasslands (1.30 per cent) > unburnt site (1.29 per cent > scrubland (1.22 per cent) > forest (1.16 per cent). The soil microbial biomass carbon also varied from 155.5-172.9 µg g⁻¹ soil in forest, 131.3-147.1 µg g⁻¹ soil in grassland, 130.4-145.1 µg g⁻¹ soil in scrubland and 174.2-186.4 µg g⁻¹ soil in non- fire site. In general the forest fires had a significant and positive effect on nitrogen mineralization and microbial biomass carbon.

Signature of Major Advisor

Countersigned

Signature of the Student

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