Impact of Prescribed fire on Nitrogen Mineralization in Three Different Ecosystems of North-western Himalayas: An Insurance to Wildfire-prone Ecosystems

Sakshi Vishvamitera*, Uday Sharma, Abhinav Guleria, [1]Ramesh Chauhan

Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Solan, Himachal Pradesh, India-173230

[1]CSIR-Institute of Himalayan Bioresource Technology, Palampur, Himachal Pradesh-176061

***Corresponding author**

E-mail Address**: sakshivishvamitera@gmail.com**

Abstract

Nitrogen affects primary productivity in natural ecosystems, thus understanding the dynamics of nitrogen pools and how they change in response to prescribed fire is crucial for management of forests and other terrestrial ecosystems. Therefore, a study on impact of prescribed fire on ammonification, nitrification and soil net nitrogen mineralization under four land uses *viz.*, Chir Pine forest (*Pinus roxburghii*), grassland, scrubland and non-fire site in Chir Pine (control) at three soil depths (0-5 cm, 5-10 cm and 10-15 cm) for a period of one year was carried out. The experiment consists of five replications in a factorial randomized block design. A prescribed fire of moderate intensity was induced in the month of March, 2018 and soil samples were taken before and after the fire at monthly intervals (April, 2018 to March, 2019) for a period of twelve months. Results revealed that ammonification rate increased initially for a period of few months post-fire up to rainy season, and then showed a declining trend in all the burnt landuses, and decreased with increasing soil depth. The ammonification was found the highest (23.18 mg N kg^{-1} $month^{-1}$) under burnt Chir Pine forest, while unburnt Chir Pine recorded the lowest rate (-0.08 mg N kg^{-1} $month^{-1}$) of ammonification. The nitrification rate stayed almost the same as pre-fire levels in the initial few months after fire, and then started mounting from August onwards till the end of study period. Burnt Chir Pine forest recorded the highest nitrification rate (32.78 mg kg^{-1} $month^{-1}$) and unburnt Chir Pine recorded the lowest (0.80 mg kg^{-1} $month^{-1}$). Nitrification was found the highest at 10-15 cm soil depth because of leaching losses. Post-fire, the net nitrogen mineralization was found the highest with a mineralization rate of 0.09 mg N $kg^{-1}day^{-1}$ in burnt forest at 10-15 cm depth as well as in grassland at 0-5 cm and 5-10 cm soil depth. However, in unburnt Chir Pine forest, net immobilization (-1.4 mg N kg^{-1}) was found at 0-5 cm soil depth. Prescribed fire accelerates the rate of net N mineralization, and therefore N availability in all the burnt landuses over control, which contributes to ecosystem productivity. Thus, our study may

make a valuable contribution towards understanding and predicting the implications of prescribed fire in the management of fire-prone terrestrial ecosystems.

Keywords: Ammonification, Chir pine forest, Grassland, Nitrification, Nitrogen mineralization, Prescribed fire, Scrubland.

Introduction

Forest habitats, which cover 31% of the total land surface, are an important nutrients reservoir in terrestrial ecosystems[1]. They are indispensable in the global nutrient cycles. Nitrogen (N) availability is regarded as the primary constraint to plant growth and development[2]. N mineralization and nitrification are two of the most critical internal ecosystem processes that influence inorganic N availability to plants and microorganisms[3]. N cycling affects not only soil conditions, but also correlated to number of environmental issues including soil acidification, nutrient leaching, and N_2O emissions[4]. Burning summers and less yearly rainfall due to climate change have increased the frequency and severity of wildfires across the world in the recent years[5,6]. Climate change prediction models revealed that wildfires would be more frequent and intense in the next decades. As per the reports of Forest Survey of India[7], it has been estimated that in India, during 2018, a total of 37,059 active forest fire events were occurred, which indicated a 1.5 times increase in the forest fires when compared to the year 2012. In India, wildfires wreak havoc on nearly around 3.73 million hectares of forest area each year[8]. Forest fires significantly stresses the terrestrial habitats, resulting in serious casualties and economic losses[9,10]. Plants and surface soil N are consumed by wildfires, resulting in contraction of the N pool in a flamed forest[11] and a subsequent drop in N mineralization rates[12].

The fire impacts on region are dependent on the intensity and duration of fire[13]. Fire can be a destructive force or a management tool, depending on how we define it. Recently the use of prescribed fires has been gaining popularity as a tool to reduce the occurrence and the impact of wildfires by reducing fuel availability. Prescribed fire is the systematic planned use of fire of low intensity under predetermined weather, fuel and topographic parameters to achieve defined objectives[14,15]. Prescribed burning affects structure and productivity of ecosystem and may directly or indirectly alter the biogeochemical cycles, including N cycling[16].

In North-Western Himalayas, particularly in Himachal Pradesh, more than 50% of the total forest area is subjected to frequent annual fires. During the period of 2016-2017, nearly 1,200 to 2,500 forest fires have been reported affecting thousands of hectares of land area[7] (FSI, 2019). Therefore, prescribed burnings are generally carried out for preventing wildfires, particularly in Chir Pine forest by state forest department. Chir Pine forests (*Pinus roxburghii*), spread in the Western Himalayas and Shiwaliks ranges at an elevation of 450-1800 meters above sea level, are particularly more susceptible to fires during summers as they shed resin containing needles making these forests highly inflammable by providing ample source of fuel to wildfires[17]. Chir Pine are huge trees (reach 30-50 m in height) having diameter of up to 2 m. The fire frequency in these forests is very high, generally repeats every year. In grasslands and scrublands adjoining the Chir Pine forests, prescribed fires are induced with the objective to prevent shrub encroachment and fuel load in grassland, and invasion and spread of exotic species in scrubland, which may also resulting in wildfire in adjoining forest. Although, the aboveground N fluxes to the atmosphere from the combustion of floral biomass following prescribed fire have been well documented[18-20], however, uncertainties remain concerning the temporal responses of belowground soil N pools that hamper our ability to comprehensively assess the effects of prescribed fire as a management tool in preventing wildfire in fire-prone ecosystems and predict ecosystem functioning following fires. In order to fill this knowledge gaps, this study was carried out, and to the best of our knowledge, this examination would be the first of its kind in India, especially in Himachal Pradesh to determine the effect of prescribed fire in terms of temporal variations on ammonification, nitrification and net nitrogen mineralization under three different ecosystems at three soil depths.

Materials and methods

Study Site

The research was carried out at Solan district of Himachal Pradesh, India during 2018-2019. The experimental sites comprised of Burnt Chir Pine forest, grassland, scrubland and control (unburnt Chir Pine area adjoining same burnt Chir Pine plantations) under the Department of Silviculture and Agroforestry, Dr. YS Parmar University of Horticulture and Forestry, Nauni. The region is located (30º52′ North latitude and 77º11′ East longitude) at an elevation of about 1260 mean above sea level (masl). The research site falls under the sub-temperate, sub-humid agro-climatic zone-II, and receives an average annual rainfall of approximately 1115 mm (about 3/4 of it is received during the mid-June to mid-September). First significant rainfall event after setting of prescribed fire occurred in the month of June (190.0 mm).Winter rains are scanty, mainly received during the month of January and February. May-June are the hottest and December-January are the coldest months. The spring season ranged from mid-February to mid-April. Geologically, the area is a part of the outer Himalayas. The soil is derived from inferakasol which comprised of calcareous shales, dolomitic limestone with bands of intermittent shales[21].The soil under tree/grass vegetation are particularly shallow with very poorly developed loamy texture. According to Soil Taxonomy of USDA, the soils of the experimental sites fall in the order Inceptisol and sub group Eutrochrept. The agrometeorological data of the study area (March, 2018- March, 2019) is given in Fig 1.

Experimental Design and Prescribed fire specifications

Four representative sites depicting three different ecosystems *viz.* Burnt Chir Pine forest, grassland, scrubland and a control of non- fire Chir Pine site were selected (Fig. 2). The experiment was laid out in a factorial randomised block design having five replications. Prescribed burning was set in the month of March, 2018, before noon hour as per the prescription parameters established for Chir Pine forest, grassland and scrubland of a study site by qualified firefighters under the supervision of officials of Himachal Pradesh Forest Department. The maximum temperature recorded was 24.3°C and no rainfall event during 15 days prior to prescribed burning occurred. Mean evaporation was of 59.5 mm with a wind speed of less than 10 km h^{-1} in the month of setting of prescribed fire. Maximum flame height was 1.2 m with a flame length of 1.7 m, and fire spread was 0.52 ha h^{-1}. The initial soil properties (0-5 cm, 5-10 cm and 10-15 cm soil depth) are given in Table 1. (Insert Table 1 below this line).

Soil Sampling and Analysis

After one month of prescribed fire, prior to soil sampling in the burnt plots, all the leaf litter was removed from the soil floor. After that, for a depth reference, a ruler was penetrated into the soil and mineral layers were carefully scrapped from the topsoil using a steel spatula at 0–5, 5-10 and 10-15 cm depth, and soil samples were collected at monthly intervals for a period of 12 months (April, 2018 to March, 2019) from a square delimited plot size of 50m × 50m, from the same place from where pre-fire soil samples were taken in order to avoid sampling errors for the study of ammonification, nitrification and net N mineralization. Each sampling square was about 5m apart from the neighbouring square. Soil samples were taken from the unburnt Chir Pine forest area (control) for a period of 12 months in a similar way. The samples were air-dried, crushed in wooden pestle mortar, passed through 2-mm sieve and then used for further analysis.

For the determination of inorganic fractions of N, aliquot was prepared. For preparation of hydrolysate, 3g of soil was shaken with 30ml of 2N KCl for 1 hour and filtered. The extract was then stored in refrigerator and was further used for extraction of ammoniacal-nitrogen (NH_4^+-N) and nitrate- nitrogen (NO_3^- -N) as per the method given by Black[22]. For the determination of NH_4^+-N, steam distillation of 10-20 ml aliquot was done along with 0.2 g MgO. Distillate of about 30 ml was collected in a beaker containing 20 ml of boric acid-mixed indicator solution, which was further titrated with 0.005 N H_2SO_4. After removal of NH_4^+-N, 0.2 g of Devarda alloy and 1 ml of sulfamic acid solution were added to destroy nitrite. Distillate of about 30 ml was collected, which was further titrated with 0.005 N H_2SO_4 for determination of NO_3^- -N.

The net increase in NH_4^+-N and NO_3^--N was used to indicate ammonification and nitrification, respectively. The net N mineralization (per month basis) was calculated by simple subtraction of NH_4^+-N+NO_3-N values of succeeding month from their preceeding months[23]. The soil net N mineralization rate was estimated by adopting the formula[24] which is as follows:

$$N_{min} = (N_2 - N_1)/d,$$

where, N_{min} is soil net N mineralization rate (mg kg $^{-1}$d^{-1}), N_1 is the initial inorganic N content (NH_4^+-N +NO_3^--N) before incubation, N_2 is the final inorganic N content (NH_4^+-N + NO_3^--N) after incubation; d is the incubation days (d).

Statistical Analysis

Data generated from laboratory studies on ammonification, nitrification and net N mineralization were analysed using two-way analysis of variance split plot (ANOVA) with two factors (landuses and months post- fire) under factorial randomized block design at 5% level of significance as per the model suggested by Panse and Sukhatme[25]. The data recorded was also analysed using MS-Excel, OPSTAT (online statistical analysis software) and SPSS 16.0 package software.

Results and Discussion

Soil Physico-chemical properties

One year post-prescribed fire, no significant differences in soil texture and bulk density were observed. Our results are in conformity with that of Tan et al[26]; Phillips et al[27]; Grady and Hart[28]; Pierson et al.[29] and Meira-Castro et al[30]. In contrast, some other studies reported significant change in soil texture[31,32], and higher or reduced values of bulk density after prescribed fire[33-35] Soil pH and EC was found to increase slightly from their pre-fire levels in all the burnt landuses, which varied from 2.92% to 5.61% and 3.24% to 4.12% after one year of prescribed fire which might be due to the addition of ash rich in basic cations and salts[36-38]. Available N, P and K content were also found to increase marginally one year post-fire, which varied from 0.47% to 3.67%, 0.21% to 2.96%, and 0.95% to 3.21%, respectively, which might be due to the release of basic cations, ash formation and mineralisation of organic forms of nutrients[39].However, the changes in soil physico-chemical properties were not statistically significant. The very low values of per cent change indicated 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. Our results arein confirmation with the findings of Binkley et al[40]; Arocena and Opio[41]; Gundale et al[42] and Valkó et al[43].

Ammonification

The data pertaining to temporal and spatial variations in ammoniacal-nitrogen content post-fire at different soil depths is given in Table 2. Significant difference in ammonification rate was observed post-prescribed fire. It ranged from 14.5 mg N kg^{-1} $month^{-1}$ to 23.18 mg N kg^{-1} $month^{-1}$ in burnt Chir Pine forest, 11.98 mg N kg^{-1} $month^{-1}$ to 17.23 mg N kg^{-1} $month^{-1}$ in grassland and 11.68 mg N kg^{-1} $month^{-1}$ to 16.68 mg N kg^{-1} $month^{-1}$ in scrubland soil. At 0-5 cm soil depth (Fig. 3 a), the highest ammonification rate (23.18 mg N kg^{-1} soil) was found under burnt Chir Pine forest in the month of July, 2018 (rainy season), while the lowest (-0.08 mg N kg^{-1} soil) was recorded under unburnt Chir Pine forest (control) in the month of January, 2019. At 5-10 cm and 10-15 cm soil depth [Fig. 3(b), 3(c), respectively], a similar trend was observed in terms of spatial variations as that of 0-5 cm soil depth *viz.*, burnt Chir pine site recorded the highest (21.74 and 19.28 mg N kg^{-1} soil, respectively) in the month of July, 2018, whereas, control recorded the lowest (-1.2 and -1.96 mg N kg^{-1} soil) in the month of January, 2019 and February, 2019, respectively. On comparing different depths, the highest increase in ammonification rate was recorded under 0-5 cm depth (62.7%), followed by 5-10 cm (38.3%) and 10-15 cm soil depth (17.5%).

Analysis of data revealed that ammonification rate increased only in the immediate months following fire for a short period of time, particularly in the months of rainy season which could be due to sudden rise in soil temperature caused by prescribed fire in the initial few months resulting in favorable soil micro-climatic conditions leading to thermal decomposition of organic N[44-52], and thereafter, it showed a diminishing trend in all the burnt landuses and ultimately tended to reach the pre-fire levels by the end of study period which might be attributed to the washing off of nutrient-rich ash layer through runoff and wind[53], microbial immobilization, and assimilation of NH_4^+-N by plants[54]. Higher ammonification rate in burnt Chir Pine site compared to grassland and scrubland could be due to rapid burning of piles of highly inflammable resin containing needles leading to more protein hydrolysis and destructive distillation of organic

N[55,56], and significant increase during rainy season might be resulted from higher temperature favouring the ammonification, whereas, decrease during winter season could be due to low temperature, a limiting factor for ammonification[57]. The higher ammonification rate in surface layers of soil as compared to the sub- surface layer might be attributed to volatilization of organic N from the soil and its further condensation in surface soil layers due to their downward movement. Moreover, surface layer of soil was typically more exposed to fire, while deeper soil layers insulated from it, therefore, combustion imparts much stronger effects on the thermal decomposition of organic matter in this layer. Our results corroborate the findings of Knoepp and Swank[58]; Prieto- Fernandez et al[59] and Nave et al[60].

Nitrification

The temporal and spatial variations in NO_3^- -N content post-fire are depicted in Table 3, and significant impact of prescribed fire on nitrification rate was recorded. The nitrification rate post-prescribed fire ranged from 0.72 mg $kg^{-1}month^{-1}$ to 32.78 mg kg^{-1} $month^{-1}$ in burnt Chir Pine forest, 0.98 mg kg^{-1} $month^{-1}$ to 24.76 mg kg^{-1} $month^{-1}$ in grassland and 1.04 mg kg^{-1} $month^{-1}$ to 27.12 mg kg^{-1} $month^{-1}$ in scrubland. In terms of temporal variations, the highest nitrification rate was observed (32.78 mg kg^{-1} $month^{-1}$) in the month of March, 2019 (Spring season), while the lowest (0.80 mg kg^{-1} $month^{-1}$**)** was observed in the month immediately following prescribed fire *i.e.*, April, 2018. At 0-5 cm depth [Fig. 4(a)], the highest nitrification rate was recorded under Burnt Chir pine forest (26.02 mg kg^{-1} $month^{-1}$), whereas, unburnt Chir Pine site recorded the lowest (-2.36 mg kg $month^{-1}$). Similar trend was observed in terms of landuses for other two depths *viz.*, 5-10 cm and 10-15 cm [Fig. 4(b), 4(c) respectively] as that of 0-5 cm soil depth.

When different depths were compared, the highest nitrification rate was observed at 10-15 cm soil depth, being 25.9% and 7.2% higher than 0-5 cm and 5-10 cm soil depth, respectively.

Post-fire, the nitrification rate was low in the starting few months in all the burnt landuses, which could be attributed to lower initial population of nitrifiers as the fire might have significantly reduced their count and hence, the period of incubation was insufficient for their significant expansions, and later on, it showed a hiking trend which might be due to conversion of increased NH_4^+-N content by nitrification, destruction of nitrification inhibitors and enhanced count of nitrifiers as the time progresses since fire[61-66]. The highest nitrification rate in the spring season could be attributed to the favourable soil conditions *viz.*, temperature, optimum oxygen and moisture content, and soil pH for nitrification. Among all the land uses, higher nitrification rate under burnt Chir Pine forest might be due to the development of optimum conditions of soil temperature and pH required for the rapid conversion of ammoniacal form of nitrogen to nitrate nitrogen as well as increased ammonification rate. This corroborates with the findings of Prieto-Fernandez et al[59]. Higher nitrification rate in deeper soil layers is ought to the fact that there was no inactivation of nitrifying microbial population because the temperature hit in this layer was not high enough and furthermore, the occurrence of rain which took place amidst the fire and the sampling may result in leaching of NO_3^--N from the surface layers to deeper one[67,59].

Net N mineralization

The significant difference in net N mineralization following prescribed fire in burnt landuses over control was recorded. In burnt Chir Pine forest, one year post-fire, net N mineralization ranged from 25.3 mg kg^{-1} to 33.3 mg kg^{-1}, whereas in grassland and scrubland, it ranged from

28.4 mg kg^{-1} to 33.0 mg kg^{-1} and 26.1 mg kg^{-1} to 31.4 mg kg^{-1}, respectively (Fig. 5). Net N mineralization on per day basis ranged from 0.06% to 0.09% in burnt Chir Pine forest, 0.04% to 0.09% in grassland, 0.01% to 008% in scrubland and -0.04% to 2.2% in unburnt Chir Pine site. Net N mineralization rate was found the highest under burnt Chir Pine forest (0.09%) at 10-15 cm depth, and grassland (0.09%) at 0-5 cm and 5-10 cm soil depths. It was observed that burnt sites had higher net N mineralization as compared to unburnt sites which might be due to the deposition of organic matter and non-uniformity in burnings resulting inin higher rates of net N mineralization. Our results arein conformation with the findings of several other studies[68-70]. In contrast, some other studies reported higher rates of net N mineralization in unburnt sites than in burnt sites[71-73]. Moreover, the contribution of ammonification towards net N mineralization was found higher (30%) than the nitrification. Similar results were reported by Nardoto and Bustamante[49]. However, some scientists claimed that the nitrification is the dominant process in N mineralization[74]. In unburnt chir pine site, net immobilsation (-1.4 mg kg^{-1}) was occurred at 0-5 cm soil depth, which might be due to increased uptake of N from the soil by microbes. This corroborates the findings of Singh et al[75].

Conclusion

From the present study, it was concluded that prescribed fire had a positive impact on ammonification as well as nitrification, though for a shorter period of time. Ammonification rate increased immediately post-fire and peaked with the start of rainy season, and declined thereafter, while nitrification rate remained same as pre-fire levels initially for a few months post-fire, and then increased and peaked during the months of spring season. Prescribed fire accelerated the rate of net N mineralization in all the burnt landuses over control, thus, enhanced the availability of N which plays an important role in determining the primary productivity of ecosystems. Considering the positive effect of prescribed fire on N availability and, consequently on ecosystem productivity, it can be used as an effective management strategy to control wildfires which otherwise can cause severe damage to the biodiversity and economic losses as well.

Funding: This study was not funded by any organization or person.

Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no conflict of interest.

References:

1. Keenan, R.J., G. A. Reams, F. Achard, J. V. de Freitas, A. Grainger and E. Lindquist. 2015. Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment. *Forest Ecology and Management* 352: 9-20.

2. Tian, P., J. Zhang, C. Mueller, Z. Cai and G. Jin. 2018. Effects of six years of simulated N deposition on gross soil N transformation rates in an old-growth temperate forest. *Journal of Forestry Research* 29: 647-656.

3. Owen, J., H. B. King, M. K. Wang and H. L. Sun. 2010. Net nitrogen mineralization and nitrification rates in forest soil in northeastern Taiwan. *Soil Science and Plant Nutrition* 56(1): 177-185, DOI: 10.1111/j.1747-0765.2009.00427.x

4. Gruber, N. and J.N. Galloway. 2008. An Earth-system perspective of the global nitrogen cycle. *Nature* 451: 293-296.

5. North, M. P., S. L. Stephens, B. M. Collins, J. K. Agee, G. Aplet, J. F. Franklin and P. Z. Fulé. 2015. Reform forest fire management. *Science* 349 (6254): 1280-1281. 10.1126/science.aab2356.

6. Murthy, K.K., S.K. Sinhab, R. Kaulb and S. Vaidyanathanc. 2019. A fine-scale state space model to understand drivers of forest fires in the Himalayan foothills. *Forest Ecology and Management* 432: 902–911. https://doi.org/10.1016/j. foreco.2018.10.009.

7. Forest Survey of India, Ministry of Environment Forest and Climate Change, Dehradun, Uttarakhand, India. https://fsi.nic.in/forest-report-2019?pgID=forest report, 2019.

8. Chandra, K. K. and A.K. Bhardwaj. 2015. Incidence of forest fire in India and its effect on terrestrial ecosystem dynamics, nutrient and microbial status of soil. *International Journal of Agriculture and Forestry* 5(2): 69-78. 10.5923/j.ijaf.20150502.01

9. Calkin, D.E., J. D. Cohen, M. A. Finney, and M. P. Thompson. 2014. How risk management can prevent future wildfire disasters in the wildland-urban interface. *In: Proc. Natl. Acad. Sci. U. S. A.* 111: 746–751

10. Bowman, D.M., G. J. Williamson, J. T. Abatzoglou, C. A. Kolden, M. A. Cochrane and A. M. Smith. 2017. Human exposure and sensitivity to globally extreme wildfire events. *Nature Ecology and Evolution* 1: 0058.

11. Hyodo, F., S. Kusak, D. Wardle and M. Nilsson. 2013. Changes in stable nitrogen and carbon isotope ratios of plants and soil across a boreal forest fire chronosequence. *Plant Soil* 364(1-2): 315-323. https://doi.org/10.1007/s11104-012-1339-8

12. Dannenmann, M., E. Díaz-Pinés, B. Kitzler, K. Karhu, J. Tejedor, P. Ambus, A. Parra, L. Sánchez-Martin, V. Resco, V Ramírez, *et al.* 2018. Postfire nitrogen balance of Mediterranean shrublands: Direct combustion losses versus gaseous and leaching losses from the postfire soil mineral nitrogen flush. *Global Change Biology* 24(10): 4505–4520. https:// doi.org/10.1111/gcb.14388

13. Shakesby, R. and S. Doerr. 2006. Wildfire as a hydrological and geomorphological agent. *Earth Science-Reviews* 74(3-4): 269-307. https://doi.org/10.1016/j.earscirev.2005.10.006

14. Cawson, J.G., P. Nyman, H. G. Smith, P. N. Lane and G. J. Sheridan. 2016. How soil temperatures during prescribed burning affect soil water repellency, infiltration and erosion. *Geoderma* 278: 12–22

15. Fuentes, L., B. Duguy and D. Nadal-Sala. 2018. Short-term effects of spring prescribed burn ing on the understory vegetation of a Pinus halepensis forest in Northeastern Spain. *Science of the Total Environment* 610: 720–731.

16. Fonseca, F., T. de Figueiredo, C. Nogueira and A. Queirós. 2017. Effect of prescribed fire on soil properties and soil erosion in a Mediterranean mountain area. *Geoderma* 307: 172–180.

17. Kumar, M., Sheikh, M. A., J. A. Bhat and R. W. Bussmann. 2013. Effect of fire on soil nutrients and under storey vegetation in Chir Pine forest in Garhwal Himalaya, India. *Acta Ecologica Sinica* 33: 59-63

18. Holdo, R. M., M. C. Mack and S. G. Arnold. 2012. Tree canopies explain fire effects on soil nitrogen, phosphorus and carbon in a savanna ecosystem. *Journal of Vegetation Science* 23(2): 352–360. https:// doi.org/10.1111/j.1654-1103.2011.01357.x

19. Pellegrini, A. F. A., W. A. Hoffmann and A. C. Franco. 2014. Carbon accumulation and nitrogen pool recovery during transitions from savanna to forest in central Brazil. *Ecology* 95(2): 342–352. https:// doi.org/10.1890/13-0290.1

20. Van der Werf, G. R., J. T. Randerson, L. Giglio, T. T. Van Leeuwen, Y. Chen, B. M. Rogers, M. Mu, M. J. E. Van Marle, D. C. Morton, G. J. Collatz, R. J. Yokelson and P. S. Kasibhatla. 2017. Global fire emissions estimates during 1997–2016. *Earth System Science Data* 9(2): 697– 720. https://doi.org/10.5194/essd-9-697-2017

21. Rao, G. 1998. Studies on dynamics of herbage layer in pine and khair based natural silvipastoral system in north-west Himalaya. Ph.D. Thesis, Dr. YSP University of Horticulture and Forestry, Solan (HP).

22. Black, C. A. 1965. *Methods of soil analysis*. Part II. *Chemical and mineralogical properties*. American society of Agronomy, Madison, Wisconsin, USA.

23. Duran, J., A. Rodriguez, J. Maria, J. Palacios and Gallardo A. 2009. Changes in net N mineralization rates and soil N and P pools in a pine forest wildfire chronosequence. *Biology and Fertility of Soils* 45(7): 781-788. https://doi.org/10.1007/s00374-009-0389-4

24. Zhou, C. and H. Ouyang. 2001. Influence of temperature and moisture on soil nitrogen mineralization under two types of forest in Changbai mountains. *Journal of Applied Ecology* 12(4): 505-508. PMID: 11758370

25. Panse, V. G. and P. V. Sukhatme. 2000. *Statistical Methods for Agricultural Workers*. Indian Council of Agricultural Research, New Delhi. pp. 381

26. Tan, K.H., B. F. Hajek, I. Barshad, and A. Klute. 1986. *Thermal analysis techniques*. Methods of Soil Analysis. 1. Physical and Mineralogical Methods. American Society of Agronomy and Soil Science Society of America, Madison, WI, pp. 151–183

27. Phillips, D.H., J. E. Foss, E. R. Buckner, R. M. Evans and E. A. FitzPatrick. 2000. Response of surface horizons in an oak forest to prescribed burning. *Soil Science Society of America Journal* 64: 754–760.

28. Grady, K.C. and S. C. Hart. 2006. Influences of thinning, prescribed burning, and wildfire on soil pro cesses and properties in southwestern ponderosa pine forests: a retrospective study. *Forest Ecology and Management* 234: 123–135.

29. Pierson, F.B., P. R. Robichaud, C. A. Moffet, K. E. Spaeth, C. J. Williams, S. P. Hardegree and P. E. Clark . 2008. Soil water repellency and infiltration in coarse-textured soils of burned and unburned sagebrush ecosystems. *Catena* 74 (2): 9.

30. Meira-Castro, A., R. A. Shakesby, M. J. Espinha ,S. Doerr, J. P. Meixedo, J. Teixeira and H.I. Chaminé. 2014. Effects of prescribed fire on surface soil in a Pinus pinaster plantation, northern Portugal. *Environmental Earth Sciences* 73 (6): 3011–3018

31. Afif, E. and P. Oliveira, P. 2006. Efectos del fuego prescrito sobre el matorral en las propiedades del suelo. Investigación agraria. *Sistemas y recursos forestales* 15(3): 262–270.

32. Granged, A.J.P., A. Jordán, L. M. Zavala, M. Muñoz-Rojas and J. Mataix-Solera. 2011. Short-term effects of experimental fire for a soil under eucalyptus forest (SE Australia). *Geoderma* 167–168: 125–134.

33. Kennard, D.K. and H. L. Gholz. 2001. Effects of high-intensity fires on soil properties and plant growth in a Bolivian dry forest. *Plant Soil* 234: 119–129.

34. Hubbert, K.P., H. K. Preisler, P. M. Wohlgemuth, R. C. Graham and M. G. Narog. 2006. Prescribed burning effectson soil physical properties and soil water repellency in a steep chaparral watershed, southern California, USA. *Geoderma* 130 (3–4): 284–298.

35. Chief, K., M. H. Young and D. S. Shafer. 2012. Changes in soil structure and hydraulic properties in a wooded- shrubland ecosystem following a prescribed fire. *Soil Science Society of America Journal* 76: 1965–1977.

36. Scharenbroch, B.C., B. Nix, K. A. Jacobs and M. L. Bowles. 2012. Two decades of low-severity pre scribed fire increases soil nutrient availability in Midwestern, USA oak (Quercus) forest. *Geoderma* 183-184: 89–91.

37. Switzer, J.M., G. D. Hope, S. J. Grayston and C. E. Prescott. 2012. Changes in soil chemical and biolog ical properties after thinning and prescribed fire for ecosystem restoration in a Rocky Mountain Douglas-fir forest. *Forest Ecology and Management* 275: 1–13.

38. Alcañiz, M., L. Outeiro, M. Francos, J. Farguell and X. Úbeda. 2016. Long-term dynamics of soil chemical properties after a prescribed fire in a Mediterranean forest (Montgrí Massif, Catalonia, Spain). *Science of the Total Environment*. https://doi.org/10.1016/j.scito tenv.2017.09.144

39. Guinto, D.F., Z. H. Xu, A. P. N. House and P. G. Saffigna. 2001. Soil chemical properties and forest floor nutrients under repeated prescribed burning in eucalypt forests of South-East Queensland, Australia. *New Zealand Journal of Forestry Science* 31(2): 172-187.

40. Binkley, D., D. Ritcher, M. B. David and B. Caldwell. 1992. Soil chemistry in a loblolly/longleaf pine forest with interval burning. *Ecological Applications* 2 (2): 157–164.

41. Arocena, J.M. and C. Opio. 2003. Prescribed fire-induced changes in properties of sub-boreal forest soils. *Geoderma* 113: 1–16.

42. Gundale, M.J., T. H. DeLuca, C. E. Fiedler, P. W. Ramsey, M.G. Harrington and J. E. Gannon. 2005. Restoration treatments in a Montana ponderosa pine forest: effects on soil physical, chemical and biological properties. *Forest Ecology and Management* 213: 25–38.

43. Valkó, O., B. Deák, T. Magura, P. Török, A. Kelemen, K. Tóth, R. Horváth, D. D. Nagy, Z. Debnár, G. Zsigrai, I. Kapocsi and B. Tóthmérész. 2016. Supporting biodiversity by prescribed burning in grasslands—a multi-taxa approach. *Science of the Total Environment* 572: 1377–1384.

44. Wilbur, R. and N. Christensen. 1983. Effects of fire on nutrient availability in a North Carolina Coastal Plain Pocosin. *American Midland Naturalist* 110(1): 54-61. https://doi.org/10.2307/2425213

45. Adams, M. and P. Attiwill. 1986. Nutrient cycling and nitrogen mineralization in eucalyptus forests of southeastern Australia-II: indices of nitrogen mineralization. *Plant Soil* 92(3): 341-362. https://doi.org/10.1007/BF02372483

46. Stock, W. and O. Lewis. 1986. Soil nitrogen and the role of fire as a mineralizing agent in a South African coastal fynbos ecosystem. *Journal of Ecology* 74(2): 317-328. https://doi.org/10.2307/2260257

47. Covington, W., L. DeBano and T. Huntsberger. 1991. Soil N changes associated with slash pile burning in pinyon-juniper woodlands. *Forest Science* 37(1): 347-355. https://doi.org/10.1093/forestscience/37.1.347

48. Monleon, V., K. Cromack, and J. Landsberg. 1997. Short- and long-term effects of prescribed underburning on nitrogen availability in ponderosa pine stands in central Oregon. *Canadian Journal of Forest Research* 27(3): 369-378. https://doi.org/10.1139/x96-184

49. Nardoto, G. and C. Bustamante. 2003. Effect of fire on soil nitrogen dynamics and microbial biomass in savannas of Central Brazil. *Pesquisa Agropecuaria Brasileira* 38(8): 955-962. https://doi.org/10.1590/S0100204X2003000800008

50. Certini, G. 2005 Effects of fire on properties of forest soils: a review. *Oecologia* 143(1): 1–10. https://doi.org/10.1007/s00442-004-1788-8

51. Turner, M., A. Smithwick, K. Metzger, D. Tinker and H. William. 2007. Inorganic nitrogen availability after severe stand-replacing fire in the Greater Yellowstone ecosystem. *In: Proc. National Academy of Sciences of the United States of America* 104(12): 4782-4789. www.pnas.orgcgidoi10.1073pnas.0700180104

52. Stirling, E., R. J. Smernik, L. M. Macdonald and T. R. Cavagnaro. 2019. The effect of fire affected *Pinus radiata* litter and char addition on soil nitrogen cycling. Science of the Total Environment 664: 276-282. https://doi.org/10.1016/j.scitotenv.2019.01.316

53. Ellingson, L. J., J. B. Kauffman, D. L. Cummings, R. L. Jr. Sanford and V. J. Jaramillo. 2000. Soil N dynamics associated with deforestation, biomass burning, and pasture conversion in a Mexican

tropical dry forest. *Forest Ecology and Management* 137(1–3): 41–51. https://doi.org/10.1016/S0378-1127(99)00311-4

54. Kaye, J. P., S. C. Hart, R. C. Cobb and J. E. Stone. 1999. Water and nutrient outflow following the ecological restoration of a ponderosa pine-bunchgrass ecosystem. *Restoration Ecology* 7(3): 252–261. https://doi.org/10.1046/j.1526-100X.1999.72018.x

55. Katterer, T., M. Reichstein, O. Anren and A. Lomander. 1998. Temperature dependence of organic matter decomposition: A critical review using literature data analyzed with different models. *Biology and Fertility of Soils* 27: 258-262

56. Eghball, B. 2000. Nitrogen mineralization from field-applied beef cattle feedlot manure and compost. *Soil Science Society of America Journal* 64: 2024-2030.

57. Bhuyan, S. I., O. P. Tripathi and M. L. Khan. 2014. Effect of season, soil and land use pattern on soil N-mineralization, ammonification and nitrification: A study in Arunachal Pradesh, Eastern Himalaya. *International Journal of Environemntal Sciences* 5:1.

58. Knoepp, J. and W. Swank. 1993. Site preparation burning to improve southern appalachian pine-hardwood stands: N responses in soil, soil water, and streams. *Canadian Journal of Forest Research* 23 (10): 2263-2270. https://doi.org/10.1139/x93-280

59. Prieto-Fernandez, A., M. Villar, M. Carballas and T. Carballas. 1993. Short-term effects of a wildfire on the nitrogen status and its mineralization kinetics in an Atlantic forest soil. *Soil Biology and Biochemistry* 25(12): 1657-1664. https://doi.org/10.1016/0038-0717(93)90167-A

60. Nave, L. E., E. D. Vance, C. W. Swanston and P. S. Curtis. 2011. Fire effects on temperate forest soil C and N storage. *Ecological Applications* 21(4): 1189–1201. https://doi.org/10.1890/10-0660.1

61. Christensen, N. 1973. Fire and nitrogen cycle in California chaparral. *Science* 181(4094): 66-68. 0.1126/science.181.4094.66

62. Wan, S. Q., D. F. Hui and Y. Q. Luo. 2001. Fire effects on nitrogen pools and dynamics in terrestrial ecosystems: a meta-analysis. *Ecological Applications* 11(5):1349–1365. https://doi.org/10.1890/1051-0761(2001)011[1349:FEONPA]2.0.CO;2

63. Ilstedt, U., R. Giesler, A. Nordgren and A. Malmer 2003. Changes in soil chemical and microbial properties after a wildfire in a tropical rain forest in Sabah, Malaysia. *Soil Biology and Biochemistry* 35(8): 1071– 1078. https://doi.org/10.1016/S0038-0717(03)00152-4

64. Andersson, M., A. Michelsen, M. Jensen and A. Kjøller. 2004. Tropical savannah woodland: Effects of experimental fire on soil micro organisms and soil emissions of carbon dioxide. *Soil Biology and Biochemistry* 36(5): 849–858. https://doi.org/10.1016/j.soilb io.2004.01.015

65. Zhang, M., W. Wang, D. Wang, M. Heenan and Z. Xu. 2018. Short-term responses of soil nitrogen mineralization, nitrification and denitrification to prescribed burning in a suburban forest ecosystem of subtropical Australia. *Science of the Total Environment* 642: 879-886. https://doi.org/10.1016/j.scitotenv.2018.06.144

66. Shubham, U. Sharma, and A. Chahal. 2021. Effect of forest fire on ammonification and nitrification: A Study under Chir Pine (Pinus roxburghii) forest areas of Himachal Pradesh. *Indian Journal of Ecology* 48(2): 376-380.

67. Raison, R. 1979. Modifications of the soil environment by vegetation fires, with particular reference to nitrogen transformations: A review. *Plant Soil* 51(1): 73-108. https://doi.org/10.1007/BF02205929

68. Hossain, A., R. Raison, and P. Khanna. 1995. Effects of fertilizer application and fire regime on soil microbial biomass carbon and nitrogen, and nitrogen mineralization in an Australian subalpine eucalyptus forest. *Biology and Fertility of Soils* 19(2-3): 246-252. https://doi.org/10.1007/BF00336167

69. Dijkstra, F. A., M. Jenkins, V. de rémy de Courcelles, C. Keitel, M. M. Barbour, Z. E. Kayler and M. A. Adams 2017. Enhanced decomposition and nitrogen mineralization sustain rapid growth of Eucalyptus regnans after wildfire. *Journal of Ecology* 105: 229–236. https://doi.org/10.1111/1365-2745.12663.

70. Albert-Belda, E., M. Belén Hinojosa, V. A. Laudicina, R. García-Ruiz, Beatriz Pérez and J. M. Moreno. 2022. Previous fire occurrence, but not fire recurrence, modulates the effect of charcoal and ash on soil C and N dynamics in Pinus pinaster Aiton forests. *Science of the Total Environment* 802: 149924. https://doi.org/10.1016/j.scitotenv.2021.149924

71. Blair, J.M. 1997. Fire, N availability, and plant response in grasslands: a test of the transient maxima hypothesis. *Ecology* 78: 2359–2368.

72. Romanya, J., P. Casals and V. R. Vallejo. 2001. Short-term effects of fire on soil nitrogen availability in Mediterranean grasslands and shrublands growing in old fields. *Forest Ecology and Management* 147: 39–53.

73. Zhou, L., J. Huang, F. Lu and X. Han. 2009. Effects of prescribed burning and seasonal and interannual climate variation on nitrogen mineralization in a typical steppe in Inner Mongolia. *Soil Biology and Biochemistry* 41: 796-803.

74. Chapin III, F. S. I., H. A. Mooney and M. C. Chapin. 2002. *Principles of Terrestrial Ecosystem Ecology*. Springer-Verlag, New York. https://doi.org/10.1007/978-1-4419-9504-9

75. Singh, J., A. Raghubanshi, R. Singh and S. Srivastava. 1989. Microbial biomass acts as a source of plant nutrients in dry tropical forest and savanna. *Nature* 388(6215): 499-500. https://doi.org/10.1038/338499a0

Table 1 Initial values of soil pH, Electrical Conductivity (ds m^{-1}), Bulk Density (Mg m^{-3}), Ammoniacal-N (mg kg^{-1}) and Nitrate-N (mg kg^{-1}) under different land uses prior to the initiation of fire

Depths Properties and Land uses	0-5 cm	5-10 cm	10-15 cm
Soil pH			
Chir pine forest	5.8	5.9	5.9
Grassland	6.1	6.2	6.4
Scrubland	6.1	6.3	6.5
Unburnt chir pine	5.8	5.9	5.9
Electrical Conductivity			
Chir pine forest	0.44	0.46	0.47
Grassland	0.51	0.53	0.54
Scrubland	0.52	0.54	0.54
Unburnt chir pine	0.44	0.46	0.47
Bulk Density			
Chir pine forest	1.11	1.12	1.14
Grassland	1.13	1.14	1.16
Scrubland	1.14	1.15	1.16
Unburnt chir pine	1.11	1.12	1.14
Ammoniacal-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

Table 2: Ammoniacal-nitrogen content post-prescribed fire at different depths (April, 2018-March, 2019)

Months (M)	0-5 cm				Mean	5-10 cm				Mean	10-15 cm				Mean
	BC	G	S	UBC		BC	G	S	UBC		BC	G	S	UBC	
April, 2018	110.82	96.72	95.58	94.14	99.32	106.10	94.12	93.40	92.96	96.65	105.06	93.52	92.38	91.92	95.72
May, 2018	112.38	97.54	97.06	93.66	100.16	108.88	96.82	95.84	90.06	97.90	106.80	95.06	94.98	92.49	97.33
June, 2018	114.64	99.50	98.76	92.96	101.47	111.44	97.78	96.98	89.64	98.96	107.04	96.70	95.08	90.08	97.23
July, 2018	116.96	100.80	99.14	94.48	102.85	113.34	98.90	98.14	91.12	100.8	108.88	97.78	96.52	92.22	98.85
August, 2018	111.18	99.12	99.28	94.80	101.10	110.40	96.52	96.12	92.49	98.88	105.98	94.44	93.42	92.64	96.62
September, 2018	106.84	98.24	96.18	95.66	99.23	105.98	96.08	95.78	92.92	97.69	101.58	93.42	92.38	93.32	95.18
October, 2018	104.78	97.90	95.42	95.18	98.32	101.58	95.08	94.44	92.52	95.91	99.28	91.92	90.92	92.16	93.57
November, 2018	101.58	97.26	94.32	95.42	97.15	99.94	94.98	92.64	93.42	95.25	96.18	89.14	88.38	91.80	91.38
December, 2018	99.28	98.24	92.38	94.98	96.22	98.24	94.02	91.44	92.22	93.98	95.42	88.74	87.58	93.32	91.27

January, 2019	96.18	95.84	90.26	93.86	94.04	95.42	93.32	90.08	94.28	93.28	93.02	86.78	85.98	94.80	90.15
February, 2019	93.66	94.16	89.50	93.22	92.64	92.38	91.80	88.74	94.80	91.93	91.80	86.18	84.76	93.60	89.09
March, 2019	93.04	92.54	88.38	92.94	91.73	91.12	90.92	87.58	93.02	90.66	90.08	85.16	84.58	91.04	87.72
Mean	105.11	97.32	94.69	94.28		102.90	95.03	93.43	92.46		100.09	91.57	90.58	92.45	
$CD_{0.05}$															
M	**1.74**					**1.60**					**1.61**				
L	**1.00**					**0.92**					**0.93**				
M×L	**3.47**					**3.19**					**3.23**				

(BC= Burnt Chir Pine; G=Grassland; S=Scrubland; UBC= Unburnt Chir Pine; M= Month; L=Landuses)

Table 3: Nitrate-nitrogen content post-prescribed fire at different depths (April, 2018-March, 2019)

Months (M)	0-5 cm				Mean	5-10 cm				Mean	10-15 cm				Mean
	BC	G	S	UBC		BC	G	S	UBC		BC	G	S	UBC	
April, 2018	52.00	51.92	51.32	49.86	51.28	57.10	55.50	54.14	51.66	54.60	53.38	52.70	52.50	50.86	52.36
May, 2018	51.92	52.74	52.58	48.88	51.53	59.46	57.78	57.52	51.50	56.57	53.06	52.58	52.12	50.50	52.07
June, 2018	54.92	53.76	52.86	49.54	52.77	61.26	59.60	59.46	51.90	58.05	59.66	57.40	56.06	51.90	56.26
July, 2018	59.42	58.96	58.40	47.30	56.02	64.22	61.12	61.46	50.92	59.43	62.62	60.32	60.86	52.12	58.98
August, 2018	64.54	62.54	61.78	48.96	59.46	67.32	63.70	63.46	51.98	61.62	66.52	62.90	63.46	52.58	61.37
September, 2018	66.54	63.96	64.42	50.80	61.43	69.92	65.92	64.78	52.62	63.31	68.92	64.92	64.18	51.62	62.41
October, 2018	71.10	67.08	65.78	51.44	63.85	73.66	70.34	71.12	53.42	67.14	72.26	69.54	70.32	52.42	66.14
November, 2018	73.20	70.00	69.24	52.04	66.12	76.08	71.02	71.90	52.12	67.78	74.88	70.02	70.70	51.52	66.78
December, 2018	69.68	63.86	63.74	49.54	61.71	76.20	65.92	66.90	51.36	65.10	74.80	64.52	65.80	50.76	63.97
January, 2019	71.54	64.94	64.08	49.46	62.51	78.68	73.62	72.46	51.34	69.03	78.68	72.82	71.46	50.74	68.43
February, 2019	75.54	67.76	66.98	48.84	64.78	82.12	77.10	78.82	50.84	72.22	81.72	76.10	77.82	49.84	71.37
March, 2019	77.22	71.30	70.50	50.68	67.43	85.18	77.96	78.22	53.72	73.77	84.58	76.36	77.42	52.52	72.72
Mean	65.64	62.40	61.81	49.78		70.93	66.63	66.69	51.95		69.26	65.02	65.23	51.45	

$CD_{0.05}$			
M	**1.71**	**1.40**	**1.51**
L	**0.99**	**0.81**	**0.87**
M×L	**3.41**	**2.80**	**3.02**

BC= Burnt Chir Pine; G=Grassland; S=Scrubland; UBC= Unburnt Chir Pine; M= Month; L=Landuses)

Figure's legends

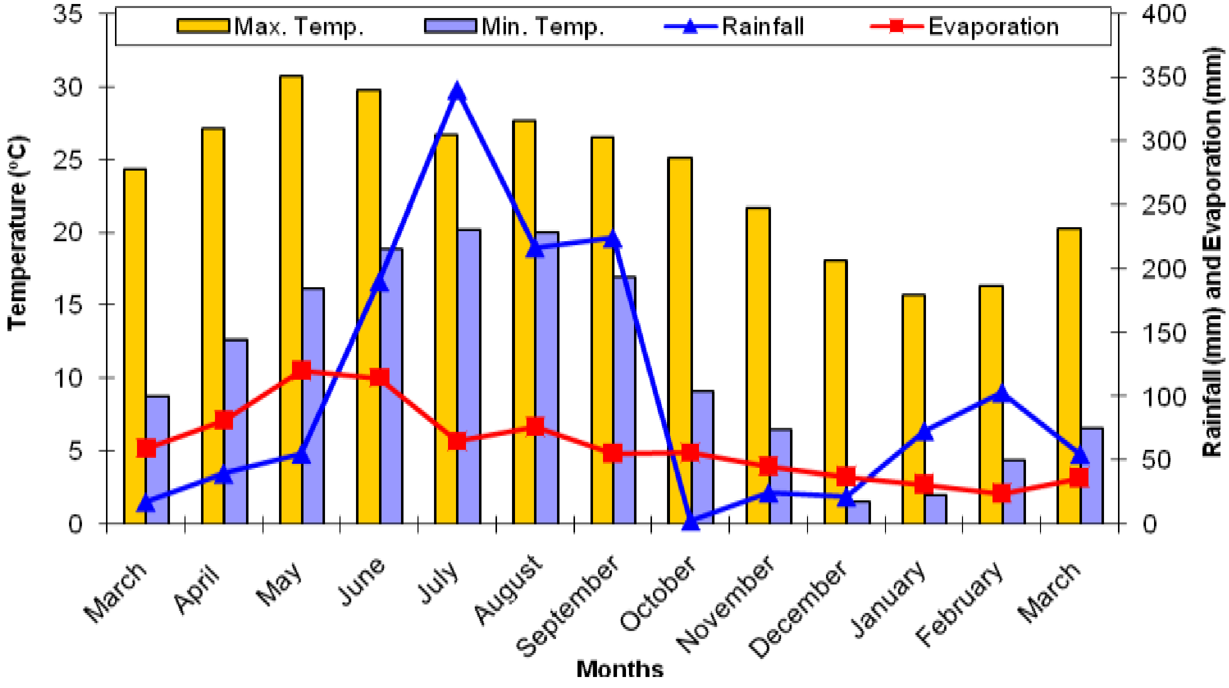
Fig. 1 Agro-meteorological data of the study area (March 2018 – March 2019)

Fig.2 Location of landuses at Dr. YS Parmar University of Horticulture and Forestry, Solan, India

Fig. 3 Ammonification (mg kg^{-1}) under different landuses at monthly intervals (a) 0-5 cm; (b) 5-10 cm; (c) 10-15 cm

Fig. 4 Nitrification (mg kg^{-1}) under different landuses at montly intervals (a) 0-5 cm; (b) 5-10 cm ; (c) 10-15 cm

Fig. 5 Net N mineralization (mg kg^{-1}) in soil under different land uses at different depths



Max. Temp.
Min. Temp.
Rainfall
Evaporation
Temperature (°C)
Rainfall (mm) and Evaporation (mm)
35
30
25
20
15
10
5
0
400
350
300
250
200
150
100
50
0
March
April
May
June
July
August
September
October
November
December
January
February
March
Months

Fig. 1


Unburned Chir Pine forest
Burned Chir Pine forest
Grassland
Shrubland
India
Solan

Fig. 2

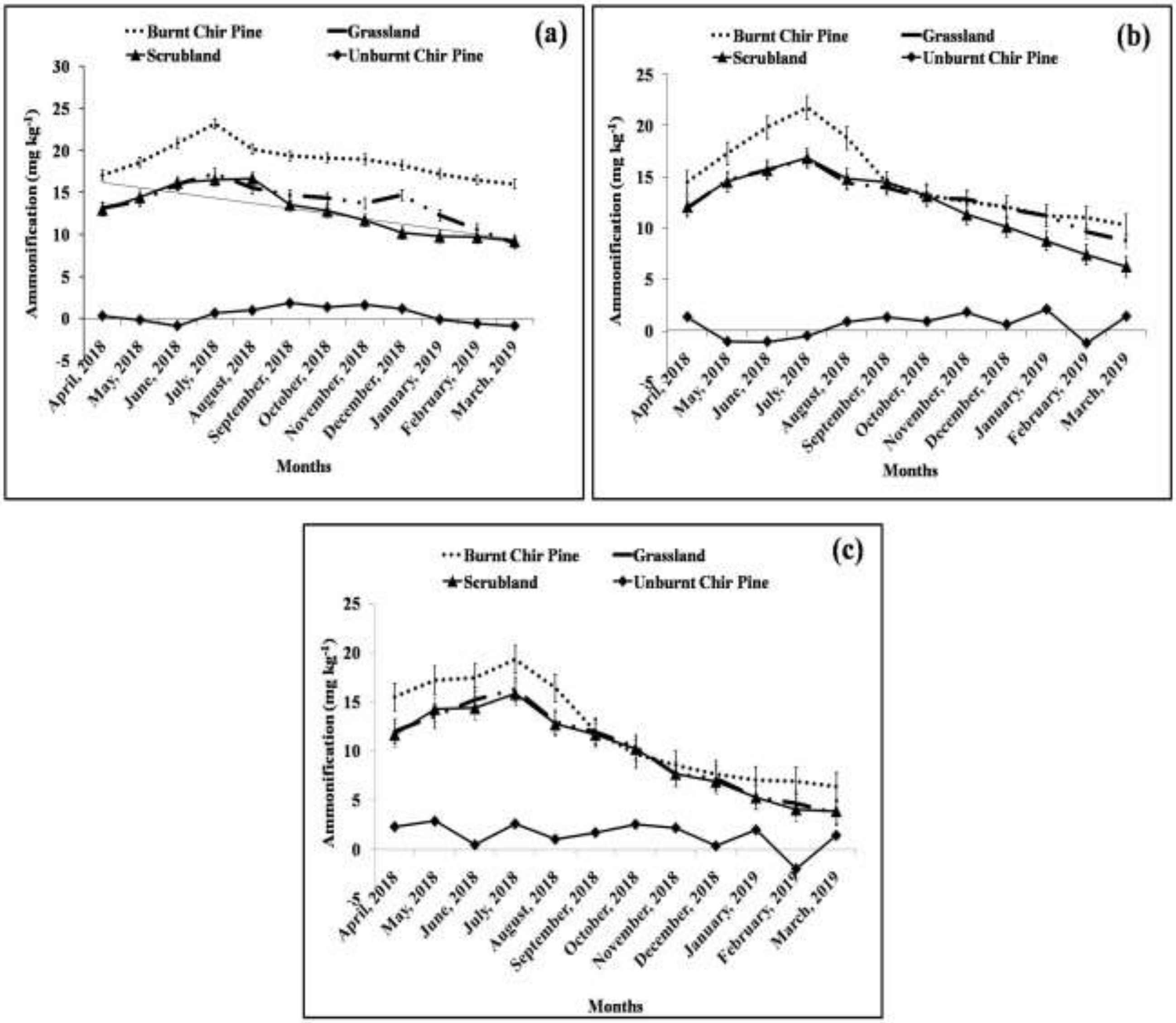

(a)
Burnt Chir Pine
Grassland
Scrubland
Unburnt Chir Pine
Ammonification (mg kg^{-1})
30
25
20
15
10
5
0
-5
April, 2018
May, 2018
June, 2018
July, 2018
August, 2018
September, 2018
October, 2018
November, 2018
December, 2018
January, 2019
February, 2019
March, 2019
Months
(b)
Burnt Chir Pine
Grassland
Scrubland
Unburnt Chir Pine
Ammonification (mg kg^{-1})
25
20
15
10
5
0
-5
April, 2018
May, 2018
June, 2018
July, 2018
August, 2018
September, 2018
October, 2018
November, 2018
December, 2018
January, 2019
February, 2019
March, 2019
Months
(c)
Burnt Chir Pine
Grassland
Scrubland
Unburnt Chir Pine
Ammonification (mg kg^{-1})
25
20
15
10
5
0
-5
April, 2018
May, 2018
June, 2018
July, 2018
August, 2018
September, 2018
October, 2018
November, 2018
December, 2018
January, 2019
February, 2019
March, 2019
Months

Fig. 3

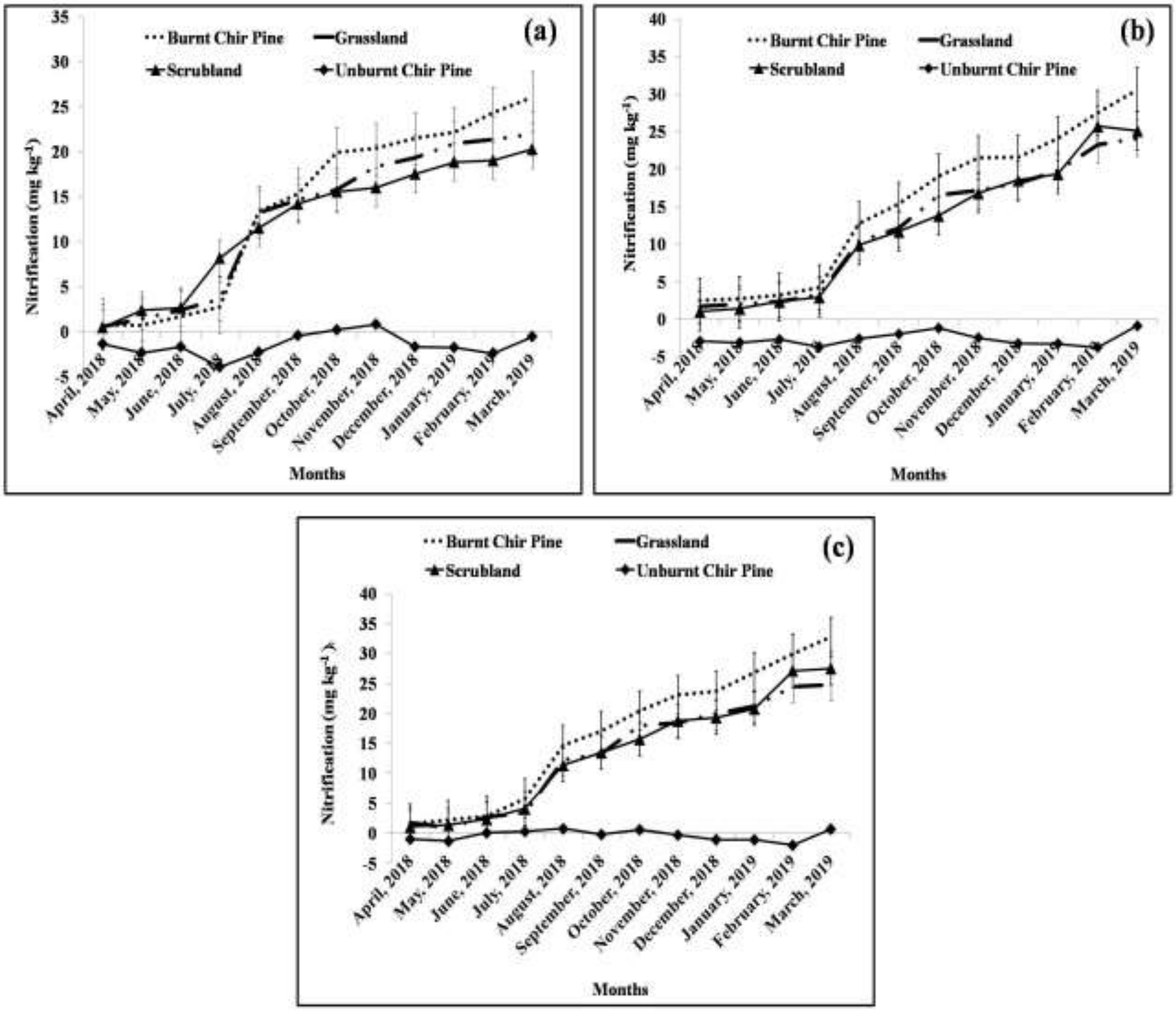
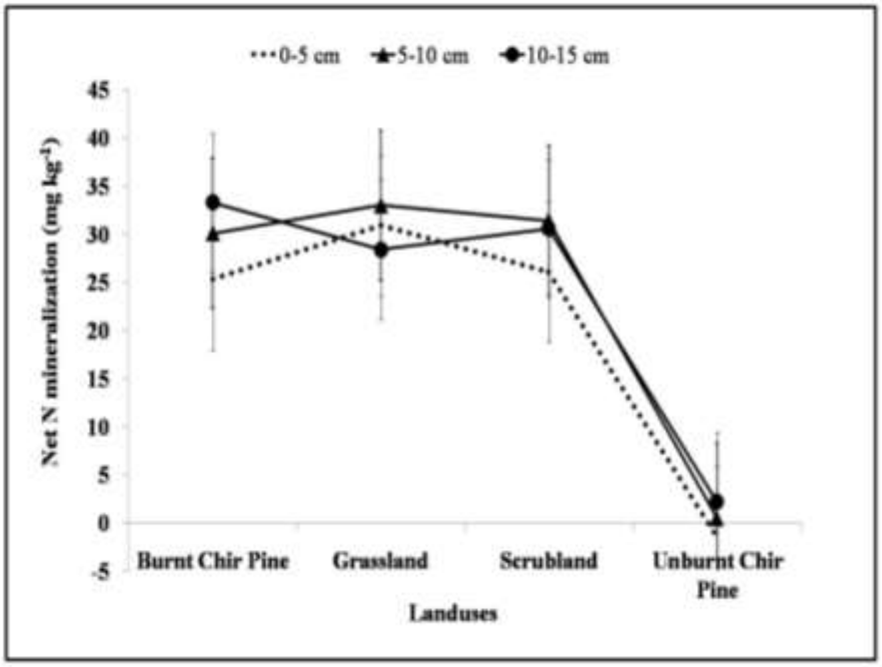

(a)
(b)
(c)
Burnt Chir Pine
Grassland
Scrubland
Unburnt Chir Pine
Nitrification (mg kg^{-1})
Months
April, 2018
May, 2018
June, 2018
July, 2018
August, 2018
September, 2018
October, 2018
November, 2018
December, 2018
January, 2019
February, 2019
March, 2019
-5
0
5
10
15
20
25
30
35
40

Fig. 4



0-5 cm
5-10 cm
10-15 cm
Net N mineralization (mg kg^{-1})
45
40
35
30
25
20
15
10
5
0
-5
Burnt Chir Pine
Grassland
Scrubland
Unburnt Chir Pine
Landuses

Fig. 5