Effects of Grassland Fire on Selected Properties of Soil in the Savannah Region of Nigeria

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Abstract

The effects of fire on soil properties have been widely studied in different ecosystems globally. However, only limited studies exist in the savanna tropics of Africa with mostly inconsistent results. The objective of this study is to characterize the effects of different fire intensities on soil properties in the Guinea Savannah of Nigeria through laboratory experiments. Three different grass species (Eleusine indica, Cynodon dactylon and Imperata cylindrica) and soils were collected from the forest zone of the University of Ilorin and prepared for laboratory investigation. Experimental fires were simulated in the laboratory to replicate field burning conditions on the prepared plots to determine precise effects of fire on soil properties. Three fire treatments (low, moderate and high) were considered, while the pre-burning and post burning samples of soils were taken for laboratory investigation, and the results statistically analyzed. The pH was observed to have increased between the range of *7.92 to 8.37. The average percentage decrease in organic matter content is 5%, 33% and 69% for low, moderate and high fire intensities, respectively. For total nitrogen, 8%, 16%, and 19% increase; calcium, 17%, 117% and 283% increase; magnesium, 11%, 30% and 84% increase; sodium, 7%, 20% and 54% increase; potassium, 24%, 20% and 49% decrease; available phosphorus, 8%, 18% and 29% increase. The results show the impacts of prescribed fire in the management of savanna ecosystem.*

Keywords: Soil properties, Savannah fires, Organic matter, Fire intensity

Introduction

Soil is an essential constituent of the earth surface that is crucial for human survival (Alcañiz *et al.*, 2018; Pereira *et al.*, 2018). The vital roles played by soils towards the stability of the ecosystem in the areas of biodiversity, climate change, food security, disease control, and a sustainable global economy cannot be overemphasized (Pereira *et al.*, 2018). The aggregate structure of a soil is significant for its optimum response that includes biogeochemical dynamics, carbon stocks, topsoil hydrology and root development (Thomaz and Fachin, 2014). Fire is identified among the agents that easily degrade the structure of a soil. This occurrence is most frequent in tropical regions with some remarkable peculiarities that make them susceptible to fire (Silva Junior *et al.*, 2018). Most often, fire causes damages on the major components of the ecosystem in addition to accelerated processes of soil degradation (Ratajczak *et al.*, 2018; Bär *et al.*, 2019; Abdulraheem *et al.*, 2020). Fire may lead to loss of nutrients by inhibiting cellulosic substances in grasses, release of toxic elements that are mostly biomarkers for diseases in humans, as well as contamination of the water table, depending on its intensity, severity and reoccurrence (Hood *et al.*, 2018; Oliveira-Filho *et al.*,

2018; Hohner *et al.*, 2019; Kowaljow *et al.*, 2019). Other important parameters of soil affected by fire include chemical and biological properties which results to the degradation of essential minerals in the soil by heat (Thomaz and Fachin, 2014; Fonseca *et al.*, 2017).

Fires are classified as prescribed fires and wildfires depending on its precipitated sources. Prescribed fires are essentially forest management practice that involve the controlled burning of herbaceous vegetation for the purpose of reducing the amount of available vegetation fuel (Bridges *et al.*, 2019) whereas wildfires occur spontaneously due to high loadings of dry fuels (Pausas and Keeley, 2019; Sayad *et al.*, 2019). The occurrence of wildfire is more frequent in the savanna regions of Africa due to the presence of highly lignified plant species (Scholes *et al.*, 2011; Gatebe *et al.*, 2014; Kouassi *et al.*, 2020), though prescribed fires are preferable to minimize the risks of wildfire due to high intensity usually accompanied with wildfire as well as other adverse influences on the soil (Fonseca *et al.*, 2017; Alcañiz *et al.*, 2018). The Guinea savanna vegetation of Nigeria experiences this kind of high intensity fires on an annual basis during dry seasons (FGN, 2019) which is discovered to be influenced by both natural and anthropogenic forces (Keeley and Syphard, 2018; Nagy *et al.*, 2018). The latter is usually aided by uncontrolled burnings in the Guinea savanna vegetation, as the locals intentionally reduce crowded plants that have little to no significant benefits during land preparation for a new planting season.

Valderrama *et al.* (2018) revealed that soil receives the most damaging effects from the outbreak of fire since it is responsible for nutrient reservoir for plant in addition to the provision of their physical support. Other physical properties of soil that may be altered during fire episodes include; pH, colour, texture, bulk density and soil biota (Quintano *et al.*, 2019). Soil aggregate properties such as aggregate stability, water repellence, water retention, soil carbon depletion and other physicochemical properties such as organic carbon, electrical conductivity, pH and organic matter (Thomaz and Fachin, 2014; Kamble, 2021) are also affected during fire episodes. The ability of the soil to recover from this kind of degradation depends on some interdependent factors such as fire characteristics, ash properties, topography, vegetation recuperation, post-fire weather and management (Pereira *et al.*, 2018). The impacts of fire on soil chemical and biological properties varies widely and is dependent on factors such as soil type, vegetation type, fire magnitude, moisture content of the soil, as well as pre and post fire environmental conditions (Alcañiz *et al.*, 2016; Ngole-Jeme, 2019).

Soil nutrients are found to be affected by series of developments during and immediately after being subjected to fire. These phases of development include ash convection, volatilization, mineralization, erosion, runoff and leaching (Neary *et al.*, 1999; Gómez-Sánchez *et al.*, 2019). Every nutritional element reacts differently to heat since each element has a specific threshold temperature, that is. the temperature where a development occurs (DeBano, 1990; Pellegrini and Jackson, 2020). Threshold temperatures of stable elements can be classified into three categories; Sensitive (Nitrogen and Sulphur with threshold temperature between 200 – 300 ℃), Moderately sensitive (Potassium and Phosphorus with threshold temperature of 774 ℃) and Relatively sensitive (Magnesium, Calcium and Manganese with threshold temperature between 1107–1962 ℃) (DeBano, 1990). Fire intensity is a measure of fuel energy which is directly proportional to the amount of fuel consumed by the fire (De Marco *et al.*, 2005). This implies that higher amounts of energy would be released from fire with a corresponding larger amount of grass species serving as fuel load during burning episodes, with the same fuel type, at similar weather conditions and uniform topography. This research study aims to characterize the effects of different magnitudes of fire on soil properties in savanna regions in Nigeria through laboratory experiments and to evaluate the potential risks of fire on certain soil conditions.

Materials and Methods

The study area selected for the collection of grass samples is located within the University of Ilorin forest zone which lies within the Guinea savanna vegetation of the country. The area has a mean annual rainfall of about 1000-1500 mm that last between 6-8 months and mean annual temperature of 28-31 ℃. The Guinea savannah vegetation is characterized by open woodland, tall grasses with growth of about 1-3 m in height and deciduous trees having exceedingly thick trunks with width of about 5 m. Fire resistant species predominate the region as a result of the region's susceptibility to extreme fires that occur mostly during the dry seasons. The soils found in the region are laterite (deeply greyish or reddish in colour) and rich lava soils that are suitable for crop productions (FGN, 2019).

Experimental fires were simulated in the laboratory to replicate field burning conditions while determining the precise effects of fire on the soil properties. The experimental method was based on previous studies of (Campo *et al.*, 2008; Bridges *et al.*, 2019). Three different species of grasses that served as fuel elements and three levels of fire intensity were specified. The burning area that was used to carry out the experiment was located within the University of Ilorin - the foundry section of the Department of Materials and Metallurgical, where safety considerations was giving the maximum priority. Three samples of mineral soil were collected from three different portions of the grassland where different grass species are dominated at; of which each portion was marked 0.25m x 0.25m and a depth of 0.1m after the removal of contaminants from the surface soils. A control sample was also collected from a random area, totalling the samples to ten (10) samples. The soils that were collected were spread evenly to reproduce the existing field conditions (Fig. 1). A representative and effective method of soil sampling where 10 cm core was taken in zigzag path to ensure adequate mixing of soil sample was applied and done for each plot (Jackson, 1958). To avoid transfer of contaminant during sample collection, the trowel was cleaned after every use.
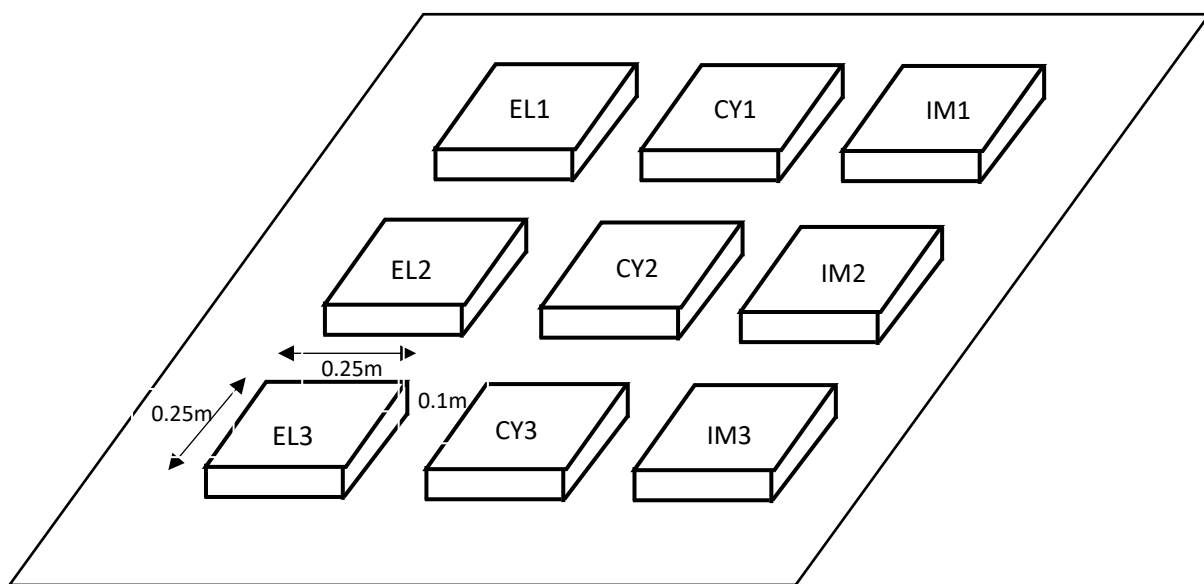

Figure 1. Schematic representation of the experimental burn plots

Three different grass species (*Eleusine indica, Cynodon dactylon, and Imperata cylindrica*) were used as fuels for the experiment at low, moderate and high density. The soils were collected at the same location as the grasses to reproduce exact field conditions. The grasses were picked from their respective locations/areas based on their density; an area of 0.25 m x 0.25 m quadrant plot was

measured around the identified grasses. Each grass specie collected was weighed to determine its mass. This procedure was repeated for all the three grass species together with their density classifications (Table 1). Each group of grasses was kindled with a propane lighter at every burning experiment. Soil samples from the post-burning experiments were collected, carefully wrapped in aluminium foil sheets and placed inside an air-tight polythene before taking to the laboratory for analyses.

Table 1. Mass of sampled grass species

Grass species	Low (g)	Moderate (g)	High (g)
	1	2	3
Eleusine Indica (EL)	15.94	18.27	41.53
Cynodon dactylon (CY)	2.76	25.24	31.28
Imperata cylindrica (IM)	8.83	41.55	78.84

The soil properties taken in the pre-and post-burning analyses include soil pH, organic matter, organic carbon, total nitrogen, exchangeable bases (Ca, Mg, Na and K) and available Phosphorus. The soil pH was determined using an electronic Jenway 3015 pH meter at a ratio of 1:2.5 (soil: water ratio). The total organic carbon in the sediment was determined using hydrogen peroxide digestion method (Schumacher, 2002). Total Nitrogen was determined using Kjeldahl method (Sáez-Plaza *et al.*, 2013). Exchangeable bases (Ca and Mg) were determined using EDTA titration method (Motsara and Roy, 2008). Available K and Na were determined using the flame photometer while available phosphorus was determined using Bray's method No. 1 (Motsara and Roy, 2008)

Results and Discussion

Soil pH
The values obtained from the results of the pH of the soil samples after burning were found to have insignificant variations for all grass species and classifications (low, moderate and high) (Fig. 2). A slight increase in pH was observed in the three grass species (EL, CY and IM) considered in the study with a range of 7.92 - 8.37. The coefficient of variation for CY, EL, and IM are 3%, 2%, and <1%, respectively. Thus, the effect of prescribed fire on the soil pH in this study is insignificant.

It was observed that an overall but insignificant increase in pH for the three sample species (fuel types) and categories at different levels of fire treatment. This is consistent with the study of (Alcañiz *et al.*, 2016) who observed an insignificant increase in pH immediately after a prescribed fire was simulated. The alteration in the pH of the soils might have resulted from the mixture of alkaline ions and oxides contained in the ash formed during post-burning operation of biotic matters that are deposited on the soil (Fonseca *et al.*, 2017). According to Bridges *et al.* (2019) significant increase in soil pH could likely be attained at burning temperature exceeding 450 ºC. This strongly explains the insignificant increase in pH observed in this study because the burning temperature was kept below the reported temperature.

Organic matter
The result obtained for the organic matter (OM) found in the soil samples shows their variations across each plot area (Table 2). Significant variations were observed according to the increased fire intensity. The average percentage decrease in OM content for EL, CY and IM species for categories 1, 2, and 3 are 5%, 33% and 69%, respectively. The organic matter contents in all the soil samples subjected to different levels of fire treatments were observed to have reduced considerably. Reduction in OM was previously reported by (Fonseca *et al.*, 2017) to have greatly reduced in low intensity fires. Likewise, in this study, organic matter in soils is also minimally impacted when exposed to low intensity fires. Although, loss of OM in soil begins slowly at lower temperature but

later results to high degradation of about of 85% when temperatures ranging between 200 – 300 ℃ is about to be reached (Tulau and McInnes-Clarke, 2015). Soil OM may be exposed to minor distillation, charring and complete oxidation depending on the intensity of the fire (Certini, 2005). Thus, factors such as fire intensity, severity, type, topography, moisture content and ecosystem determine the effects of fire on soil OM (Verma and Jayakumar, 2012; Fonseca *et al.*, 2017; Alcañiz *et al.*, 2018). In this study, it was observed that EL3, CY3 and IM3 have higher reduction in OM content compared to the other category while EL3 had the highest reduction rate in all.
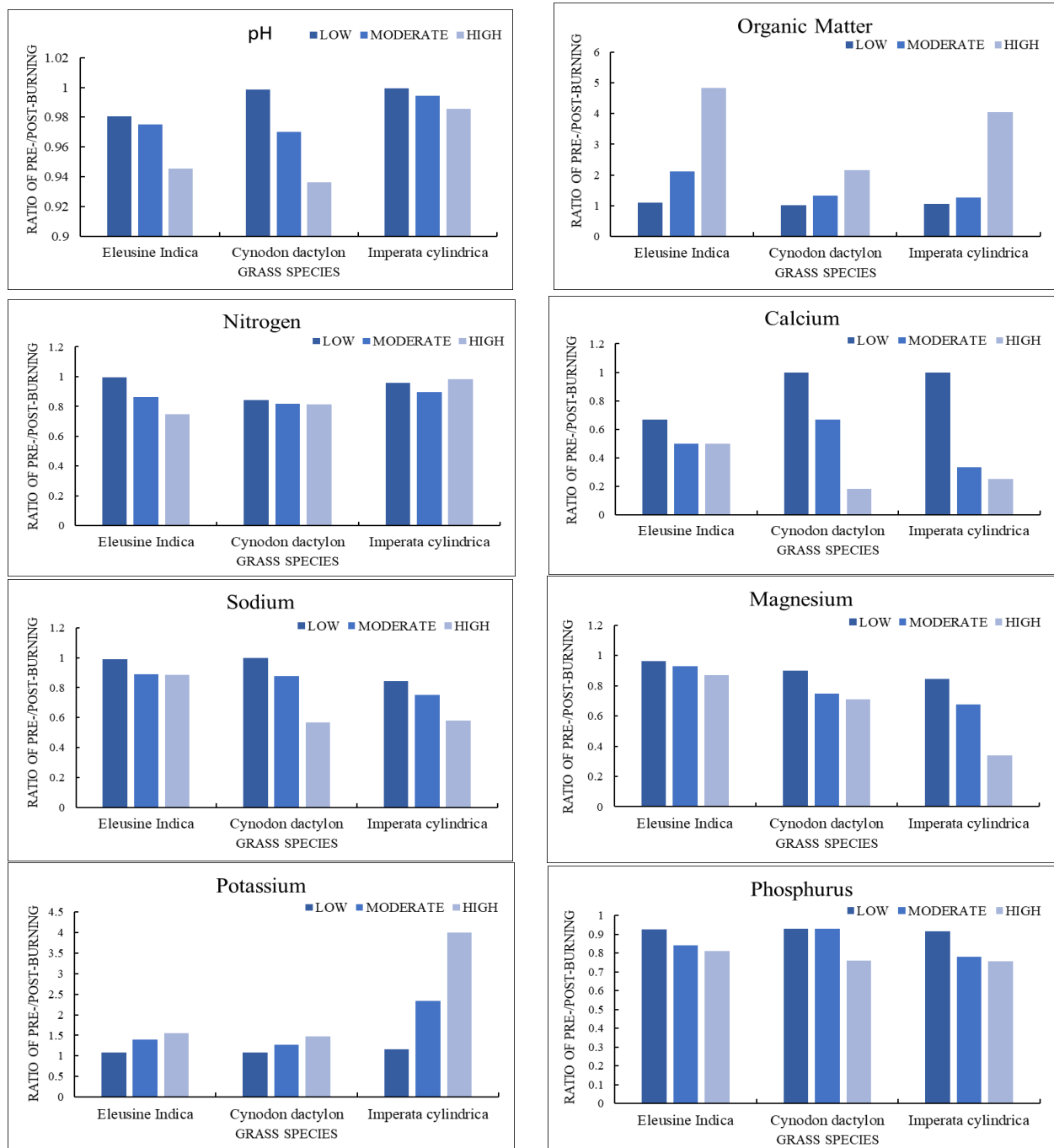
Figure 2. Ratio of pre-burning to post-burning for pH, organic matter, Nitrogen, Calcium, Sodium, Magnesium, Potassium and Phosphorus for selected grasses.

Table 2. Mean values of post-burning soil parameters in Low (1), Moderate (2) and High (3) fire intensity treatments

Soil Parameters	Eleusine indica			Cynodon dactylon			Imperata cylindrica		
	EL1	EL2	EL3	CY1	CY2	CY3	IM1	IM2	IM3
pH	8.07	9.37	8.11	8.16	8.45	7.92	8.03	7.92	7.96
OM (%)	3.01	1.32	5.81	4.79	7.95	6.22	6.05	5.00	1.57
N (%)	0.43	0.61	1.11	0.34	1.38	1.11	1.18	1.05	0.50
Ca (Cmol/kg)	0.09	0.01	0.02	0.01	0.06	0.02	0.04	0.01	0.03
Na (Cmol/kg)	0.22	0.20	0.61	0.44	0.95	0.61	0.64	0.41	0.23
Mg (Cmol/kg)	0.07	0.07	0.06	0.05	0.18	0.09	0.16	0.07	0.04
K (Cmol/kg)	0.09	0.04	0.13	0.10	0.34	0.13	0.12	0.06	0.04
P (mg/kg)	0.29	0.26	1.43	0.53	1.24	1.24	0.26	0.48	0.33

Total Nitrogen

Total Nitrogen was observed to have increased in all the sample species and categories. The average increase in the total nitrogen is found to be 8%, 16%, and 19% for EL1, CY1 and IM1; EL2, CY2 and IM2; and EL3, CY3 and IM3, respectively. The coefficient of variation for CY, EL and IM are 2%, 14% and 5%, respectively. Total nitrogen was observed to increase in all plot area, with the highest increase recorded in EL3, CY3 and IM3 due to higher fuel load (grass density). The present nitrogen compounds are likely in the forms of NH_4-N and NO_3-N which increase immediately after each fire episode (Verma *et al.*, 2019). Küçük and Kahveci (2020) reported that there is an increased N-mineralization occurring with increased fire severity for typical grassland communities. The net N-mineralization may perhaps be related to factors such as; the total nitrogen contents of the soils, unregulated burning procedures and organic matter deposition unto the soil (Nardoto and Bustamante, 2003). Earlier studies have reported a significant increase in total nitrogen immediately after prescribed fire had taken place (Alcañiz *et al.*, 2016; Reinhart *et al.*, 2016; Francos *et al.*, 2018). On the other hand, volatilization of nutrients that is precipitated by fire is also an important effect on soils. Direct loss of nutrients in the soil to the atmosphere after a fire occurrence is however dependent on burning temperature because nitrogen begins to volatilize at 200 ºC as other nutrients are found to volatilize at higher temperatures (Neary *et al.*, 1999; Wittkuhn *et al.*, 2017). At a temperature of 200 ºC or below, elemental nitrogen is slightly lost, but at higher temperature organic nitrogen is converted to ammonium ions and later to NO_3 due to nitrification which gets leached rapidly and out of the available nutrient pool (Tulau and McInnes-Clarke, 2015).

Exchangeable Bases (Ca, Mg, Na and K)

Calcium was observed to increase significantly in all the sample species and categories. The average percentage increase of 17% was observed in EL1, CY1 and IM1 while EL2, CY2 and IM2 increased at an average of 117% and EL3, CY3 and IM3 at 283%. The order of increase for calcium content in the sample species was observed from the least to the highest fire intensities; with CY3, IM3 and EL3 having values of 0.05, 0.04 and 0.02 cmol/kg, respectively. These observations implied that calcium slowly degrades with increasing fire intensity. Hence fire has substantial effect on the calcium content in the soil samples studied. Similarly, magnesium increased in all fuel types and fire treatments with an average of 11% for EL1, CY1 and IM1, 30% for EL2, CY2 and IM2; while EL3, CY3 and IM3 increased at 84%. The coefficient of variation for Mg for EL is the highest with 5%, 12% for CY and 51% for IM. Conversely, sodium levels vary across the treatments and fuel

types. The results showed an increase in Na levels for all treatments. An average increase of 7% was observed in EL1, CY1 and IM1, 20% was observed for EL2, CY2 and IM2 while EL3, CY3 and IM3 had an average increase of 54%. For Potassium (K), overall reduction was also observed in Potassium for all treatments. 24% average reduction was observed in EL1, EL2 and EL3, 20% in CY1, CY2 and CY3 while 49% in IM1, IM2 and IM3.

Available Ca, Mg and Na were higher in all the fire treatments levels and fuel types immediately after the prescribed fire. Increased nutrients after burning episodes were reported in the study of (Pereira *et al.*, 2017; Francos *et al.*, 2018) where ash deposition on the soil surface during burning is found to promote the increase of the present Ca and Mg found in the soils due to the alkalization effect (Oliveira-Filho *et al.*, 2018). However, Gómez-Rey *et al.* (2013) observed no change in Na concentrations after fire contrary to our observation in this study. Potassium content was lower in all treatments and fuel types. The effects of fire on potassium have been studied by a wide range of researchers. However, the results of these studies have been inconsistent. For instance, reduction in exchangeable K in soil immediately after fire was described by (Bridges *et al.*, 2019; Verma *et al.*, 2019; Alcañiz *et al.*, 2020) while (Kutiel and Shaviv, 1992; Lucas-Borja *et al.*, 2019) reported an increase in K immediately after burning. Pivello *et al.* (2010) have also observed that available Ca, Mg and K are not really affected by the fire but at the time of burning but by the frequency of fire in the ecosystem.

Available Phosphorus
Available phosphorus increased in all fire treatment levels. EL1, CY1 and IM1 increased with an average of 8%, EL2, CY2 and IM2 increased at 18% while EL3, CY3 and IM3 increased at 29%. The coefficient of variation for P for EL is 7%, whereas it was 12% for CY and 10% for IM. Available phosphorus increased in all the plots in this study. Significant increase in available phosphorus were observed after wildfire and experimental fire in Spain (Gómez-Rey *et al.*, 2013; Badía *et al.*, 2014). Alcañiz *et al.* (2020) reported remarkable increase in available phosphorus and concluded that the increase was caused as by high temperature burning which resulted to mineralization and OM combustion. Litton and Santelices (2003) stated that phosphorus is usually not volatilized and readily available phosphorus present in ash is integrated back into the soil after precipitation.

Conclusion
In this study, changes in soil properties were examined, to determine the effects of prescribed fire. This study revealed an increased level in the soil pH, total Nitrogen, Ca, Mg, P and Na while potassium and organic matter content decreased. The effects of fire on these soil properties are usually variable which is dependent on the magnitude of fire, moisture content, environmental conditions, and soil type. Although this study examined the immediate effects of prescribed fire on three different grass species, there is no indication that the grasses types have any influence on the parameters considered. Thus, it is recommended to advance the study to validate the influence of some other factors on the long-term effect of fire and how they individually affect soil nutrients.

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