

Article

Immediate Changes in Organic Matter and Plant Available Nutrients of Haplic Luvisol Soils Following Different Experimental Burning Intensities in Damak Forest, Hungary

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Abstract: One of the major pedological changes produced by wildfires is the drastic modification of forest soil systems properties. To our knowledge, large research gaps are currently present concerning the effect of such fires on forest Haplic Luvisols soils in Central Europe. In this study, the effects of experimental fires on soil organic matter and chemical properties at different burning intensities in a Central European forest were examined. The study was conducted at Damak Forest, in Hungary, ecosystem dominated by deciduous broadleaf trees, including the rare Hungarian oak *Quercus frainetto* Ten. The experimental fires were carried out in nine different plots on Haplic Luvisol soils transferred from Damak Forest to the burning site. Three types of fuel load were collected from the forest: litter layer, understorey and overstorey. Groups of three plots were burned at low (litter layer), medium intensity (litter and understorey) and high intensity (litter, understorey and overstorey). Pre-fire and post-fire soil samples were taken from each plot, analysed in the laboratory and statistically compared. Key plant nutrients of organic matter, carbon, potassium, calcium, magnesium and phosphorus were analysed from each sample. No significant differences in soil organic matter and carbon between pre- and post-fire samples were observed, but high intensity fires did increase soil pH significantly. Calcium, magnesium and phosphorus availability increased significantly at all fire intensity levels. Soil potassium levels significantly decreased (ca. 50%) for all intensity treatments, in contrast to most literature. Potassium is a key nutrient for ion transport in plants, and any loss of this nutrient from the soil could have significant effects on local agricultural production. Overall, our findings provide evidence that support the maintaining of the current Hungarian fire prevention policy.

Keywords: soil properties; experimental fires; nutrients; UV-spectroscopy analysis; thermal infrared thermometer

1. Introduction

Wildfires affect agricultural and forest land covers more than any other land cover type [1]. Prescribed fires involve basically controlled burning of forests as a mean to reduce fire fuel levels. This practice minimises the extent, severity and danger of potential wildfires [2]. In Europe, prescribed fire use has disappeared from many countries due to the intensification of agriculture and socio-economical changes [3]. In most European countries prescribed burning is prohibited. Where permitted (e.g., in UK, Germany, France, Spain, Slovenia), there are strict controls on the timing and

location of the burning extension. European fire management policies are still aimed at fire suppression instead of using prescribed fires as a preventative measure. At present, only 10,000 ha year⁻¹ of the Mediterranean basin is prescribed burnt; for comparison, this is about 3% of the wildfire extent in Spain, France and Portugal alone [4,5].

The use of prescribed fires in Europe is mostly an ‘unnatural’ event for both biotic and abiotic systems. Ecosystem alterations can arise as a consequence of fires, such as niche alteration for native species [6], invasion of alien species [7], and drastic changes to forest soil systems properties [2]. Climate change is an additional threat to wildfires frequency, due to projected higher mean temperatures, increase in the number of summer days and the decline of average precipitation. Climate change models suggest that by 2100, temperatures in central Europe will increase up to about 3 °C [8]. This increase in temperatures will cause soils to become drier for longer periods and therefore would extend the wildfire season globally. Southern Europe has already experienced record summer temperatures in 2017. The Intergovernmental Panel on Climate Change’s (IPCC) Fifth Report (AR5) on forest fire risk shows as a general trend that each region, below the 55th parallel north, will either increase in forest fire risk or stay at the same level [9]. Temperate forests are particularly sensitive to the effects of climate change due to their long lifespan preventing rapid adaptation. The large amount of C in forest soils means that any deviation of the level will have a significant effect on global C balance and climate change [10]. The future IPCC projections support that the effects of wildfires will be an increasing concern for both the scientific community and the governmental agencies.

A major factor influencing the effects of fires on soil properties is fire severity, a parameter primarily controlled by combustion and site factors. Combustion factors include quantity, moisture and type of fuel, whereas site factors include topography, wind direction, air temperature and humidity [2]. There are two key components of fire behaviour that influence fire severity: intensity and duration. Intensity is defined as the rate of thermal production in the fire, whereas duration is the length of time soil is exposed to fire. The most varied change to forest soils during burning is the loss of soil organic matter (OM) and plant available phosphorous and nitrogen in mineral soils. Fire severity plays a significant role in the effect on this important carbon pool. Substantial consumption of OM occurs between 200 and 250 °C and is complete at ca. 460 °C [11]. Fire does not maintain a consistent temperature in the soil. Some parts of the burn area might experience over 460 °C, whereas other areas may only experience less than 200 °C. This means that the OM may only experience minor volatilisation at low temperatures compared to complete oxidation at high temperatures. There is consensus about combustion causing reduction or total removal of the forest floor [12]. The reduction of OM is not uniform with depth: for example, some studies have found that concentrations of OM decreases significantly by the heating effect at 1 cm depth, but not at 2 and 3 cm depth in a pine forest ecosystem, North-East Spain [13].

Studies have found differences between prescribed burning and wildfire effects on soil 10 years following the fire event: i.e., lower carbon content following prescribed fire and higher soil C content following wildfire, due to the accumulation of charcoal and the encroachment of post-fire N-fixing vegetation [14]. Studies support these findings, describing, e.g., OM returning to normal after one year [13]. They also showed that fire has a fertilising effect, due to the dissolution of ashes and the mineralisation of charcoal enriching the soil.

The key nutrients within forest soils, mainly contained in its organic matter component (OM) are: nitrogen (N), available phosphorus (P), exchangeable potassium (K), exchangeable calcium (Ca) and exchangeable magnesium (Mg). Each nutrient reacts differently to fire, depending on its individual volatilisation threshold [15]. The combustion of nutrients bound in vegetation and soil organic matter add inorganic forms of K, Ca, Mg, P and N to the soil [16]. Each nutrient has its own response to burning, e.g., early studies have found that concentrations of K, Ca and Mg ions can increase, whereas N and S often decrease [17]. Fire intensity is directly linked to the temperature an object experiences during fire, which in turn impacts the type of nutrient and the amount volatilised. Fire acts as a rapid mineralising agent [18]. This mineralisation has been studied extensively for N and

P, because they are the two key macronutrients for plants. Soil nutrients that have low volatilisation thresholds are the first to be mineralised. There is an immediate reduction in soil organic N due to volatilisation [19]. Substantial proportions of soil organic N survive low intensity fires, however, moderate to high intensity fires convert most soil organic nitrogen to inorganic forms [2]. The effects of fire on properties of forest soils have been extensively reviewed and found that generally, losses of P through volatilisation are low [2]. However, the combustion of vegetation and litter cause major modifications on the P cycle. Micronutrients are also affected immediately after burning; e.g., total content and reducible forms of Mn increase significantly following fire due to the ash produced [20].

Soil pH has been also found to increase post fire. This increase has been attributed to the addition of base cations in ash, and to organic acid denaturing due to the heating of the soil [2]. However, significant increases only occur at temperatures >450 °C [21]; this temperature links with the total combustion of fuel as the ash produced has the capacity to neutralise soil acidity. Through analysing mixed forest soils, topsoil pH could increase as much as three units immediately after burning due to the production of K and Na oxides [22]. This significant increase can only be found in non-calcareous soils; calcareous soils are already alkaline, and in them the pH increases induced by fire are often negligible.

Currently, very little is known about the effect fires have on forest soils in Central Europe. Most research in Europe comes from Mediterranean forest studies, while there are few investigations about the areas that, according to the IPCC climate change scenarios, will have in the future climate similar to that of the Mediterranean region [9]. Soil in Mediterranean forests have low moisture and available nutrients, and plants are adapted by co-existing to prevent competition in resource scarce environments [23]. Field research on fires, to our knowledge, is limited in Hungary in particular. Primary research is generally on the effects to biodiversity, mainly in grasslands and based on questionnaires to fire departments [24,25]. In particular, little research has been done on the effects of fire on Haplic Luvisols in Central Europe. Luvisols occupy ca. 5% of the total continental land area on Earth, and are found mainly in west-central Russia, the United States, Central Europe, the Mediterranean and southern Australia [26].

In purview of the above, the present study objectives were to: (1) characterise the effect of different fire intensities in a burn experiment on the organic matter, pH, potassium, phosphorus, calcium and magnesium of forest Haplic Luvisol through laboratory analysis; (2) examine the effectiveness of the experimental burning design at measuring changes in soil properties, and, (3) provide recommendations for fire authorities in Hungary about potential risks to the dominant soil Haplic Luvisol from both prescribed fires and wildfires. For this purpose, a field experiment of three fire treatments on forest Haplic Luvisol in Damak forest, NE Hungary was implemented.

2. Materials and Methods

2.1. Study Area

The study was carried out in Damak forest (48°31' N, 20°82' E), in the county of Borsod-Abaúj-Zemplén, Hungary (Figure 1). The area is characterised by a temperate continental climate. The mean annual temperature of the area is 9.5 °C; warmest period ranges from May to September (20.0 °C in July). Maximum precipitation within this warm period is 82 mm (July); mean annual precipitation is 567 mm. Forest typology is classified as mixed broadleaf and coniferous woodland (Figure 2). Dominant species are Hungarian oak, common nettle *Urtica dioica* L., black locust *Robinia pseudoacacia* L., Scots pine *Pinus sylvestris* L. and hornbeam *Carpinus betulus* L.

Soils in the studied area are of the Haplic Luvisol type [27,28]. This is a non-calcareous soil, with neutral pH and high in organic matter. In stark contrast to the Hungarian Plains (80 km South-West, higher precipitation and lower temperatures in Damak forest has led to the development of this soil type. As this is a forest soil, there is an organic horizon, comprised primarily of leafy material that is separated from the mineral horizon [27]. For this study, we identified a Haplic Luvisol that to our knowledge was negligibly affected by human disturbance, at about 250 m from the experimental site.

In Damak Forest, where soil samples were collected, there have been no recent significant disturbances that could affect this study, in particular prescribed or wild fires.

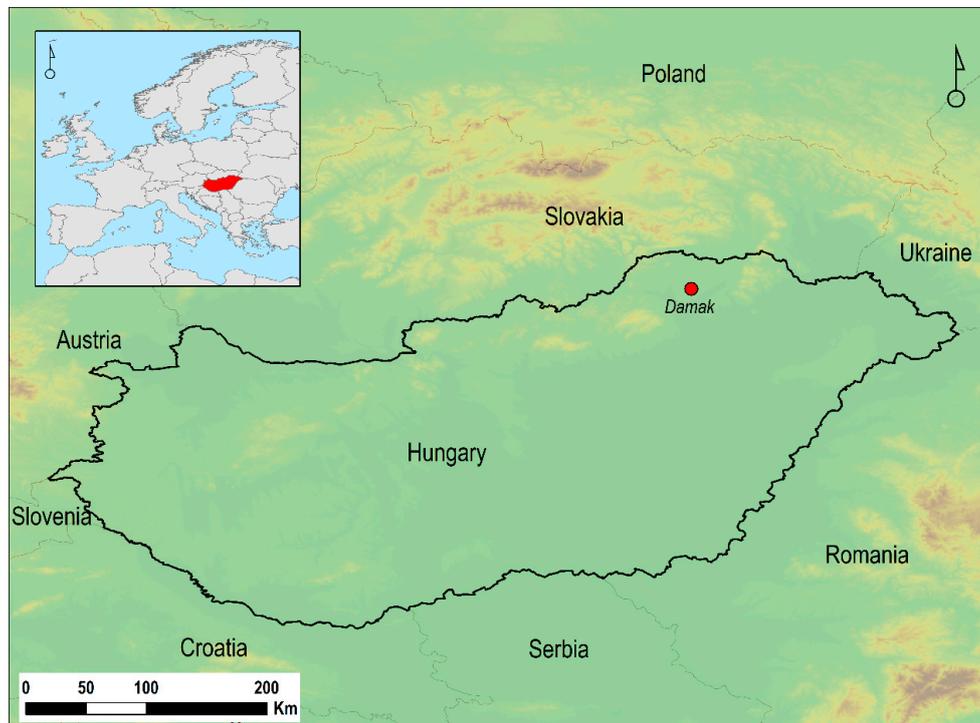


Figure 1. Study area: Damak Forest (red point; geographical coordinates 48°31' N, 20°82' E) in Borsod-Abaúj-Zemplén county, Hungary. Inset map: Hungary (red) in Europe.

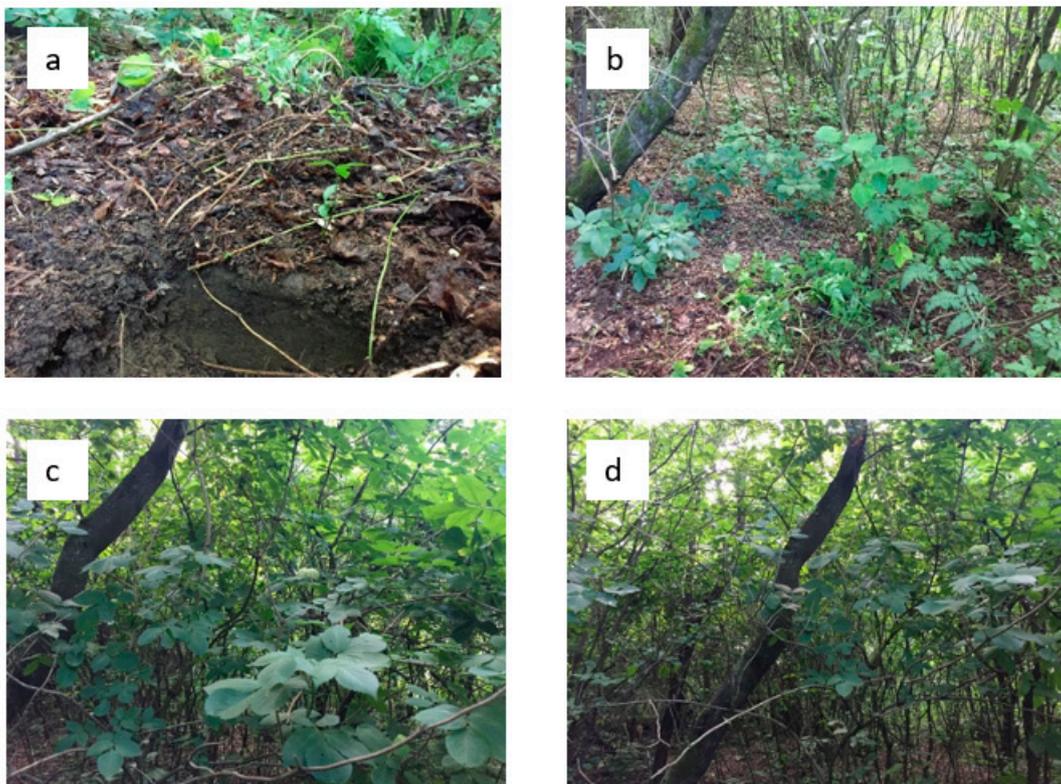


Figure 2. Characteristic vegetation and strata in Damak forest: (a) soil to litter layer interface, (b) litter layer, (c) understory and (d) overstorey. Photo: Jack M. Bridges.

2.2. Experimental Design

Experimental burning is used to simulate fire conditions in a safe area, where the effects of fire can be accurately observed. Studies using experimental burning are usually carried out between late spring and early autumn [29,30]. This is the optimum period where soil is dry and fuel is burnable. Experimental burns should recreate the same conditions as a real forest fires. One of the problems with the literature of experimental burning is that there are no universally established fuel load amounts for low, medium and high intensity fires. Studies have recommended for high and medium intensity fires, to use 40 and 20 t ha⁻¹ of fuel, respectively [31]. For smaller scale experimental burning plots this equates to a minimum of 4 kg m⁻² of fuel for high intensity and 2 kg m⁻² for medium intensity.

The experimental approach is built along the lines of previously published studies [29,30,32] measuring fire effects on soil properties on the basis of setting up experimental fires of different burning intensities. The experimental burning area in our study is located in a 1500 m² paddock, about 200 m from the source of forest soil, providing a safe area to conduct the experiment. A total of nine 0.5 × 0.5 m plots and 0.225 m³ of forest soil was transported to the area. The litter layer from the soil was removed and the upper 10 cm of mineral soil was collected. Soil was then distributed evenly to form the nine 0.1 m depth plots (Figure 3) to recreate the conditions in the forest. To prevent factors such as slope, drainage and texture affecting our results, all the soil was taken from the exact same location within Damak forest. This area was representative of the whole forest, and no single species dominated the under and overstorey, while the litter layer contained similar material to most of the forest floor.



Figure 3. Characteristics of the experiment burn plots: (a) 0.1 m depth, (b) 0.5 m width, (c) plots ($n = 9$), and (d) three plots per fuel load. Photo: Jack M. Bridges.

Three sets of three plots were burned close to the soil samples collection site with three distinct fire intensity treatments; low (F1), medium (F2) and high (F3). Three different fuel layers were used to achieve these fire intensities (Table 1), to represent degrees of heterogeneity in forest structure. The plots were ignited by a 30 s exposure from a propane torch in a circular motion around the plot. Pre-fire samples (F0) were taken from each plot for comparison. The vegetation used as the fuel load came from the same area as the soil, creating realistic conditions of a wildfire/prescribed fire. The first treatment (F1), involved the addition of ca. 4 kg m⁻² of litter layer to three plots. The second treatment (F2), ca. 12 kg m⁻² of litter layer and understory fuel was added to another three plots. In the third treatment (F3), ca. 40 kg m⁻² of litter layer understory and overstorey fuel was added to three plots (Table 2). Allocation of fire treatment to the plots was randomised to prevent pseudo-replication in a Latin square design [33].

Table 1. One-way ANOVA mean difference between low (F1), medium (F2) and high (F3) fire intensity treatments, and pre-fire (F0) for pH (soil), soil organic matter (OM), carbon (C), calcium (Ca), potassium (K), magnesium (Mg) and phosphorus (P). $n = 9$ samples for F0 and $n = 3$ samples for F1, 2 and 3 treatments. ** Significant difference at $p < 0.01$. * Significant difference at $p < 0.05$.

Treatment	F0						
	pH (soil)	OM (%)	C (mg/kg)	Ca (mg/kg)	K (mg/kg)	Mg (mg/kg)	P (mg/kg)
F1	0.03	0.53	0.50	242.00 **	190.00 **	6.00 **	0.25
F2	0.44 *	0.14	0.70	1272.00 **	190.33 **	22.00 **	33.25 **
F3	0.45 *	0.82	4.10	1452.00 **	187.33 **	13.74 **	39.7 **

Table 2. Weight of fuel for each plot.

Subplot	Weight of Litter Layer (kg)	Weight of Understorey Fuel (kg)	Weight of Overstorey Fuel (kg)	Total Fuel Weight (kg)
1A	1	0	0	1
1B	1	0	0	1
1C	1	0	0	1
2A	1	1.6	0	2.6
2B	1	1.7	0	2.7
2C	1	1.4	0	2.4
3A	1	1.2	7.2	9.4
3B	1	1.5	6.1	8.6
3C	1	1.2	6.9	9.1

Subplot 1 (A, B, C) = Low intensity fire. Subplot 2 (A, B, C) = Medium intensity fire. Subplot 3 (A, B, C) = High intensity fire.

During fire, temperatures on the surface of the soil were measured by a thermal infrared thermometer. Plot temperatures were recorded at 2 min intervals until the maximum temperature fell below 100 °C. This value was chosen as it has been shown to be the threshold temperature for the most relevant changes in soil [29,31,34].

2.3. Sample Collection and Laboratory Analysis

The remaining litter was discarded and the whole ash layer was collected and weighed from each plot; sample mean ash weight from F1 plots was 9.00 g, 36.00 g from F2 plots and 200.33 g from F3 plots. Prior to soil sampling, the litter layer was removed. An effective and representative method of soil sampling was employed. This involved taking 10 cm cores in a zigzag path across the plot and mixing to form an average sample; this was repeated for each plot [35]. The samples were taken using a trowel, and this was cleaned after each sample was taken to prevent cross-contamination. The samples were stored in a Kraft wet-strength paper bag labelled with the sample subplot and whether it was pre-fire or post-fire.

Samples were then air dried and sieved to isolate and keep the <2 mm diameter soil particles, which were then used for the analysis of chemical properties. One plot had three laboratory samples made up to improve the accuracy of the instrumentation (sample 3A).

Chemical properties analysis was then carried out in a laboratory. Organic matter content (%OM) was determined by Loss-on-Ignition (LOI). Samples were properly heated to ensure the complete loss of moisture from the soil [36,37]. F0, F1, F2 and F3 samples were then weighed (Figure A2, Appendix A). The samples were then heated to 430 °C in a muffle furnace for 16 h and weighed. This removed most of the carbon and OM [38]. By comparing the two weights before and after ignition, LOI can be calculated, which is the value for OM. C makes up ca. 50% of the OM value [39,40], therefore C was estimated by multiplying LOI by 0.5.

An acetic acid extraction (Figure A1, Appendix A) provided an estimate of the plant available content of the macro and micro nutrients contained in the samples. Using atomic absorption spectrophotometry (AAS) [41], elements Ca, Mg and K were measured (Figure A3, Appendix A). UV-visible Spectroscopy [42] was used to determine the value of P (Figure A4, Appendix A). The pH of the ash layer, F0, F1, F2 and F3 samples were measured using a Whatman pHA wet-bulb pH meter, pH obtained with water and a proportion of 1:2.5 soil to liquid (Figure A5, Appendix A).

An in-house standard reference material (ABS3) validated the precision of the sample measurements. This standard is soil based and was stored in a sealed container in cool, dark storage prior to use. All dry samples were weighted with the same mass balance to ensure consistency. Sample 3A was repeated three times and a control (blank) was used to ensure the reliability of all methods. Analysis of variance (ANOVA), at $\alpha = 0.05$, between F0 and the three post-fire samples (F1, F2 and F3) was performed to detect any significant statistical differences among results.

3. Results

3.1. Burn Characteristics

Temperatures at the soil surface during the low intensity fires (F1) averaged 228 °C. The highest temperature recorded was 400 °C. Mean burn time >100 °C was 0.79 min (Figure 4). Weight of ash averaged 11 g ($n = 3$ for all values). Due to the infrared thermometer's maximum temperature threshold of 420 °C, a true average of the soil surface temperature could not be calculated for the medium and high intensity fires. For this reason, we measured the percentage of time >420 °C. This resulted an average of 43% of the total burn time for medium intensity fires (F2). Highest temperature recorded was ≥ 420 °C. Mean burn time >100 °C was 15.98 min (Figure 4). Weight of ash averaged 36 g ($n = 3$ for all values). Temperatures at the soil surface during the high intensity fires (F3) averaged >420 °C for 85% of the total burn time. Highest temperature recorded was ≥ 420 °C. Mean burn time >100 °C was 190.67 min (Figure 4). Weight of ash averaged 200.6 g ($n = 3$ for all values).

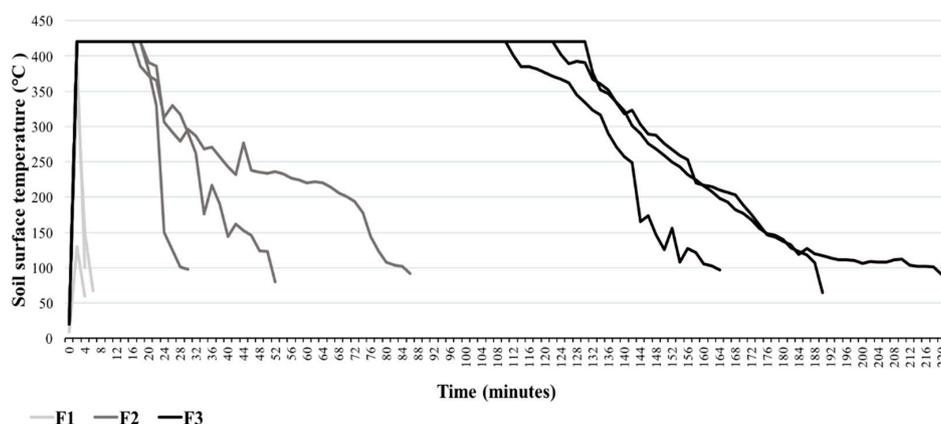


Figure 4. The burn time and soil surface temperatures of each subplot for F1, F2 and F3 treatments.

3.2. Fire Intensity Treatment Effects on Haplic Luvisol Properties

3.2.1. Soil and Ash pH

Results obtained for the pH of soil showed a slight decrease for F1 (low intensity fire treatment; Figure 5). This was followed by an increase in pH after F2 and F3 (medium and high fire treatment, respectively). F3 was significantly increased at $p > 0.05$ compared with the F0 measured pH (Table 1), F1 and F2 were not significantly different. This shows that immediately after the burn, medium and high intensity fires can change the Haplic Luvisol pH from slightly acidic to neutral. The pH of ash increased by ca. 1.0 for each treatment: F1 8.42, F2 9.79, F3 10.33. This is a dramatic change as the pH scale is logarithmic (Table 3). The coefficient of variation for F1 and F2 was 5%, whereas it was 14% for F3.

Table 3. Mean values of pH (soil and ash), soil organic matter (OM), carbon (C), calcium (Ca), potassium (K), magnesium (Mg) and phosphorus (P) in low (F1), medium (F2) and high (F3) fire intensity treatments, and pre-fire (F0). $n = 9$ samples for F0 and $n = 3$ samples for F1, F2 and F3.

Variable	F0	F1	F2	F3	Reference Material Accuracy
pH (soil)	6.39 ± 0.34	6.38 ± 0.12	7.17 ± 0.63	7.01 ± 0.36	N/A
pH (ash)	N/A	8.42 ± 0.55	9.79 ± 0.43	10.33 ± 1.54	N/A
OM (%)	6.60 ± 1.70	6.07 ± 1.88	6.74 ± 1.45	5.78 ± 1.15	N/A
C (mg/kg)	33.00 ± 8.50	33.50 ± 9.40	33.70 ± 7.25	28.90 ± 5.75	N/A
Ca (mg/kg)	2048.00 ± 39.00	2290.00 ± 47.00	3320.00 ± 78.00	3500.00 ± 12.00	97.00
K (mg/kg)	402.48 ± 0.44	212.48 ± 0.03	212.15 ± 0.03	215.15 ± 0.05	85.00
Mg (mg/kg)	25.67 ± 0.02	31.67 ± 0.05	47.67 ± 0.05	39.41 ± 0.02	59.00
P (mg/kg)	13.30 ± 2.08	13.55 ± 1.96	46.55 ± 4.75	53.00 ± 4.00	80.00

3.2.2. Organic Matter and Carbon

Results obtained for organic matter (OM) content varied greatly among the plots (Table 3). F1 and F3 lowered the OM% by a small amount (0.53% and 0.82% respectively), though not significantly (Table 1), whereas, F2 increased the amount of OM by only 0.14%. The coefficient of variation for all treatments was around 20% (Table 3). These results show that organic matter in Haplic Luvisol is not significantly affected by fire.

The carbon content of the soil samples (Table 3) remained at similar levels for F1 and F2 treatments compared to F0, 33 mg/kg. For F3, the amount of carbon decreased by 13%, from 33.00 to 29 mg/kg (Table 3). Carbon levels in the soil samples did not significantly change after any of the treatments (Table 1). Coefficient of variation was 30% for all treatments. Carbon levels in Haplic Luvisol after a fire event of any intensity are not affected.

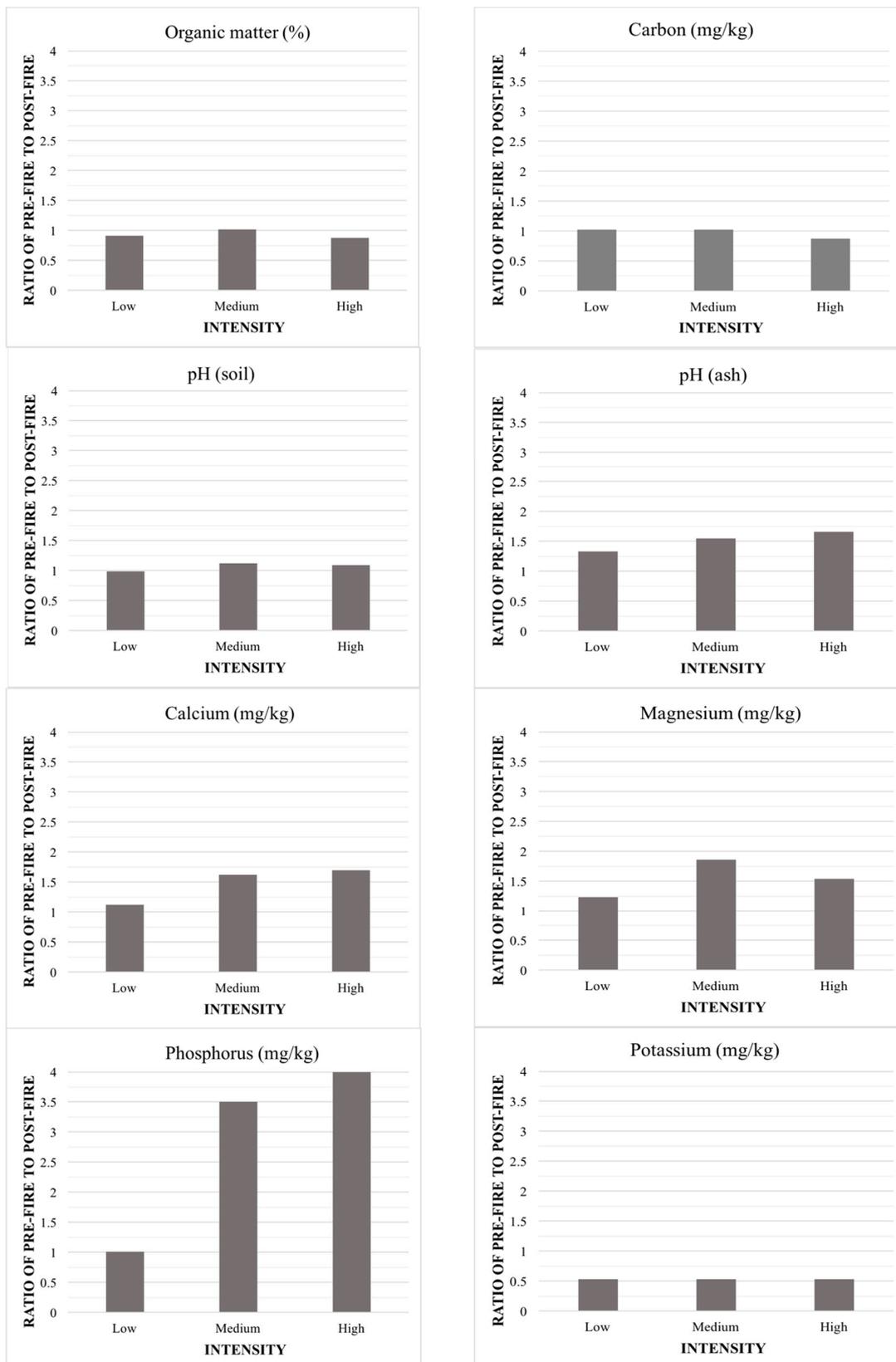


Figure 5. Ratio of pre-fire to post-fire change for pH (soil and ash), organic matter, carbon, calcium, magnesium, potassium and phosphorus. >1 = positive change, 1 = no change, <1 = negative change. Note the different scales on each graph.

3.2.3. Available calcium

Available calcium in soil increases with fire intensity (Figure 5), higher intensity fires result in more available calcium present. There was a noticeable increase after F2 and F3, over 1000 mg/kg more calcium measured than after F1 (Table 3). Each fire treatment showed a significant increase at $p < 0.01$ in comparison to F0 (Table 1). The coefficient of variation for calcium was 2% for F0, F1 and F2; while F3 was 0.3%. The reference material accuracy was 97% for calcium. This was the highest out of all the parameters measured (Table 3), meaning the accuracy of the Atomic Absorption Spectroscopy was very high. Fire therefore, has a significant effect on the amount of calcium present in Haplic Luvisol immediately after a fire event of any intensity.

3.2.4. Available Potassium

The potassium levels in the soil decreased significantly for F1, F2 and F3 at a significance of $p < 0.01$ (Table 1). The negative correlation has shown that higher intensity fires decrease the amount of potassium present in the soil immediately after the burn. The decreasing ratio is constant for all three treatments (Figure 5), dropping from 402.48 mg/kg (F0) to 212.48, 212.15 and 215.15 mg/kg (F1, F2 and F3, respectively). The coefficient of variation was; 0.11% for F0 and 0.01% for F1, F2, F3 (Table 3). Reference material accuracy was calculated at 85%, showing a high accuracy of the AAS instrumentation. Therefore, the level of potassium in Haplic Luvisol can be significantly affected by fire of any intensity immediately after the fire event.

3.2.5. Available Magnesium

Magnesium levels varied across the three treatments (Figure 5); F2 had the highest level at 47.67 mg/kg followed by F3 (39.41 mg/kg) then F1 (31.67 mg/kg) in comparison with the pre-fire level of 25.67 mg/kg. All treatments showed a significant increase in plant available magnesium at $p > 0.01$ (Table 1). The coefficient of variation was; 0.08% for F0, 0.16% for F1, 0.10% for F2 and 0.05% for F3 (Table 3). The reference material accuracy was 59%, which shows a medium accuracy of the AAS instrumentation for magnesium parameter.

3.2.6. Available Phosphorous

The higher the fire intensity, the higher the phosphorus availability. (Figure 5). The amount of P stays constant between F0 and F1, at 13 mg/kg, rising to 46.55 and 53.00 mg/kg after F2 and F3, respectively. These increases in P are significant at $p > 0.01$ (Table 1). The coefficient of variation was; 15.6% for F0, 14.5% for F1, 10.2 % for F2 and 7.5% for F3. Reference material accuracy was calculated at 80% (Table 3), this is a high accuracy for the UV-visible spectroscopy.

4. Discussion

4.1. Burn Characteristics

Recreating conditions of a natural burn, whether prescribed fire or wildfire, is one of the biggest challenges of experimental burning. The amount of biomass and type of species can dictate the intensity of the fire; the challenge is that no forest composition is the same. There are other dominating factors such as weather and topography that influence fire behaviour; weather conditions determine whether the fuel load is 'available' to burn. Weather and topography cannot be controlled in this study so therefore the focus was the effect of different fuel load and type of fuel.

For this experiment, extensive research was carried out to produce the best experimental burn design as detailed in the Materials and Methods section. Some studies [43,44] that used the same recommendations of fuel load for medium and high intensity burns, 20 and 40 t ha⁻¹ respectively, found that medium intensity fires burned for ca. 17 min and high intensity fires burned for ca. 37 min [45]. The Damak experiment followed the same fuel load recommendations; however, the mean

burn time >100 °C for F2 and F3 were 55.67 and 190.67 min, respectively. An explanation for this is could be attributed to the size of burn area; the area for one study was 105 m² [44] and another was 80 m² [43]. A larger burn area would create a more severe fire and therefore, burn at a quicker rate. These differences are possibly due to different instrumentation, being that these studies used thermocouples that measured temperature directly within the soil. Our experiment used an infrared thermometer that measured the soil surface temperature. The burning material on the soil surface would make both the burn time and temperature a higher reading compared to studies that use thermocouples due to the soils insulating properties.

4.2. Effect of Fire Intensity on Soil Properties

The pH of noncalcareous soils (such as Haplic Luvisol) should increase after burning, due to the effect of organic acid denaturisation [2] and the release of alkaline cations. Below the threshold of medium fire intensity, burning does not affect soil pH. This is likely to be due to some of the plots for F1 being at a lower pH originally compared to the average pH of all the plots pre-fire. This would mean that the F1 pH would appear to decrease compared to the pH of the plots before burning (F0). pH is not consistent in soil. Substances such as decomposing leaf litter and plant materials can have a higher pH than the underlying soil. Therefore, when F1 was applied to the soil, some of the leaf material is likely to have mixed with the soil. This would produce a higher pH for F1 plots compared to the F0. The fact that the soil sample bags were left for two months before laboratory analysis, might have been enough time for the plant material to change the original soil pH. Studies have found a decrease in pH after low intensity followed by an increase at higher intensity burn sites [32]. It is important to note that the results for F1 pH were not significantly different to F0.

The pH of F2 was higher than F0 but not significantly. However, F3 pH was significantly higher than F0. This shows that the pH after high intensity fires is significantly affected, supported by other studies [2]. Studies have found that significant increases in soil pH only occurred at temperatures >450–500 °C [21], this supports our F3 pH data. However, this shows that the maximum temperature for F2 cannot have exceeded 450 °C. Many authors report increased pH values after a prescribed fire [46].

The pH of ash above the soil for F1, F2 and F3 were significantly higher than both the original soil pH and each other. This was to be expected as the carbonates and oxides that are produced from combustion are highly alkaline. This is supported by studies that found that topsoil pH (including the ash layer), under a mixed conifer forest, increased three units immediately after the burning [22]. Our high intensity burn plots experienced an increase of six pH units within the ash layer. It is likely that ash leaching, chemicals draining from the ash into the underlying soil by the action of percolating liquid (usually rainwater), could turn the soil from slightly acidic to more alkaline. This would possibly have an effect on tree species, especially in forests like Damak. Common pine *Pinus sylvestris* and nettle would likely cope with these changes to the soil, because the latter prefers high levels of phosphate. However, species like hornbeam can only grow in neutral soils, so in the case the pH becomes too alkaline it will not be suitable for its growth. There would possibly be a profound effect on the native Hungarian oak, as they are specially adapted to heavy acidic soils. Additionally, following a forest fire in the region, invasive species such as black locust would probably pioneer alkaline rich soil: this species has a tolerable pH range of 4.6–8.2, but prefers dry alkaline soils.

The varied results for the OM and C post-fire in our experiment are supported by other studies [47]. The effect of fire on soil OM is highly dependent on a number of factors that are seen in our study including; fire intensity, varied distribution of organic matter in the soil, nature of burned vegetation. Effects have been highly variable in many studies [15,48] with effects ranging from complete combustion of organic matter to increases of up to 30%. This is a prominent discussion in soil research as there is no generalised trend between organic matter and burning, it is variable controlled. For example, soil heated under laboratory conditions have frequently reported significant losses in OM and C of up to 100% [49], whereas after a wildfire there have been records of an increase [10]. Another study suggests this could be due to the addition of necromass in forests (dead wood and organisms) after a fire event

which is not as prevalent in a laboratory experiment [50]. One study produced a comprehensive dataset of soils effected by wildfire or prescribed fire. Their study concluded that lower C content was found after prescribed fires while higher C content was found after wildfires [14]. This was attributed to the accumulation of charcoal and encroachment of post-fire N-fixing vegetation. We do, however, acknowledge the presence of some limitations due to the application of the LOI method to determine OM and OC. LOI is based on two assumptions: (1) LOI equals OM and (2) the ratio OM/OC is the same for all treatments. LOI incorporated more than just OM, for example hydrated covers of clays, which are expected to be partially lost when a thermal shock occurs, therefore LOI was not exactly equal to OM in this case. In addition, as different temperatures were reached among fire treatments, the OM/OC ratio would not be the same in all of them, likely: OM/OC ratio decreases with the thermal treatment. For these reasons, what we found in our results related to OM and OC can be mainly attributed to using a broad non-specific technique of measuring OM and OC, with its inherent limitations. Further research should imply a more precise method to determine OM and OC, like a modern dichromate oxidation method. This would ensure a precise quantification of OM and OC.

Calcium results suggest that all fire intensities significantly affect calcium levels in Haplic Luvisol. This finding is supported by other studies examining the effect of fire on Ca levels in soil [2]. As the volatilisation threshold temperature of Ca occurs at 1484 °C [15], it is relatively insensitive to fire (temperature of burning woody fuel ca. 1100 °C). Therefore, it was not expected in this study to observe any reductions in the amount of Ca. The reason why Ca increases significantly after fire is thought to have come from the mineralisation of the organic matter [32]. Studies suggest that the exchange capacity of surface horizons is depleted after fire which increases the number of cations that are not volatilised (Ca and Mg) [51].

The soil samples measured after the burnings would contain Ca released from the overlying biomass. This could be evidence as to why there was a major increase in Ca between F1 and F2/F3. The increased biomass (ca. 2 and 8 kg more for F2 and F3, respectively) would contribute much more Ca cations than 1 kg of litter (F1). Another possibility is that the temperatures in F2 and F3 reached the volatilisation threshold of K and P, ca. 750 °C [52].

The potassium (K) level after all fire treatments was significantly lower than the pre-fire levels, ca. 50% reduction. This is not supported by much of the literature measuring K levels post-fire events [2,53]. As the volatilisation of K occurs at ca. 750 °C, this reduction would be expected in very high fire intensity events, however, we have observed the reduction in F1 (low intensity) so the reduction in K cannot be attributed to volatilisation. The instrumentation accuracy was high for K (87%), so the reduction cannot be an instrumentation error. There is a possibility that being left in the soil sample bags for 2 months the K cations bound to inorganic substances; however, similar reductions would be observed in F0 if this was the case. A probable reason is that the available potassium was immobilised within mineral structures driven by thermal treatment.

There are very limited studies exploring the effect of fire on K levels in Haplic Luvisol. The studies that have been carried out support our findings that K levels are reduced, after a fire event, in Haplic Luvisol [54]. One study measured significantly lower K levels in the 0–5 cm soil layer post-fire for Umbric leptosols, attributing the loss to erosion and leaching [55]. Studies suggest available K should increase after low intensity prescribed fires [46]. However, there were no erosional or leaching processes occurring in our experiment therefore, the reason why there is a reduction of K in Haplic Luvisol is likely to be due to the composition of the soil. Another explanation could be the moisture level of the soil. It has been found that soil moisture significantly affects the availability of K [56]. The Damak soil was dry (observed in fieldwork) which could have reduced the level of K recorded. However, dry soil would be present in F0 measurements so the K values should be similar to F1, F2 and F3 K values. The results from this study show that fire was the cause of the reduction in K. The effect fire has on K levels in Haplic Luvisol is a therefore a key finding.

Mg levels post-fire were all significantly increased. This increase has been found in many post-fire soil analysis studies [2]. The volatilisation of Mg occurs at ca. 1107 °C [15] therefore there should be no

reduction in its availability post-fire. As with Ca, the increase in available Mg is likely to come from the mineralisation of the organic matter in the soil.

Following a prescribed fire, we were expecting increased available phosphorus [46]. The fact that available phosphorus increases with fire intensity can be attributed to the conversion of organic P to orthophosphate [57]. This occurs during the combustion of organic matter and is dependent on the type of soil, vegetation species and leaching [58]. We observed an increase in P for Haplic Luvisol underlying a temperate deciduous forest with no leaching (as samples were taken immediately post-fire). This increase confirms other findings in this area of soil science [59]. The general trend is that P increases significantly dependant mainly on the fire intensity [2]. Small amounts of P can be lost through volatilisation. The threshold temperature for P is ca. 774 °C [60], therefore, losses would be expected in F2 and F3 as the burn time and temperatures could reach >774 °C. However, it is important to note these losses would be very low in comparison to the converted P. In this experiment, there is a clear positive relationship between available P and fire intensity. This result has been found in many levels [2].

In relation to the changes observed in soil OM and C, were somehow inconclusive. This is likely because soil was taken at a depth of 10 cm. Therefore, there would be a dilution effect on the impact of fire on the upper soil (organic matter is mainly affected in the upper 2 cm layer). It could also depend on the amount of OM in the soil pre-fire and soil type. This is supported by other studies [10]. However, in a forest setting, organic matter has shown to return to pre-fire levels after one year [13]. Therefore, any effect of fire on the OM and C would be recoverable in the long term.

One limitation of this study was the instrumentation used to measure soil temperature. This can be observed in the burn time (Figure 4), being much longer than studies that used thermocouples [43,44]. It is likely that the infrared thermometer measured flames from the burning vegetation instead of the soil surface, thus giving the higher temperature (flame). An accurate measurement of the soil surface temperature could not be measured. Therefore, assumptions had to be made in relation to whether certain cations reached their volatilisation threshold. Ideally, a thermocouple would be used that could be inserted into the soil surface and measure the temperature. In addition to that, this study was limited to 0.5 m² plots through health and safety restrictions. With accessible funding and Government approval, larger plots could be used, as is the case in Spain, where researchers have had access to 80 m² plots [29,31]. A larger scale plot would be a better way to recreate the conditions of a prescribed fire/wildfire. Furthermore, the time between soil sample collection and analysis would ideally be as short as possible, however for our experiment, the gap between collection and analysis was two months. Samples were stored in dark and dry conditions; nevertheless, several processes could still take place within the soil. For example, the exchangeable cations released by the fire treatments could bind to inorganic substances and affect the results for that cation. The soil samples contained root systems and small amounts of vegetation. Their decomposition over two months could lower the pH through the release of carbon dioxide. However, in our study, the processes described above would have had negligible effect on our samples; pH increased in all samples and the change, for all cations measured, was significantly increased. Lastly, the same prescribed fire experiment could have also been implemented at other locations of Hungary with the same Haplic Luvisol soil type, to provide more conclusive results on the burning effect on forest Haplic Luvisol.

The immediate changes to forest soils following burning have been discussed. This study contributes to the concept that burning temperate forests in Central Europe can have a direct impact on soil fertility and forest management, whether that is from prescribed burning or wildfires. The use of small scale experimental fires to measure this effect has mirrored larger experimental burning and wildfire studies.

5. Conclusions

The main purpose of this study was to measure and analyse the immediate effect of fire on forest Haplic Luvisol. This was carried out using representative small scale fire plots that enables fire effect

on soil to be measured without damaging large areas of land. These experimental fires carried out on soil matter in Damak Forest, North East Hungary, produced significant changes to the Haplic Luvisol organic matter and chemical properties. Increased changes were most obvious in exchangeable Ca, followed by available P and exchangeable Mg, with pH only significant in the high intensity fire treatment. Significant decrease was observed in all the fire intensities for exchangeable K. This is a key finding of this study, as it is one of the few studies that have found losses in exchangeable K post-fire. This contrasts with the general behaviour of exchangeable K in soils [2,46]. As expected, a higher intensity fire resulted in a greater change in nutrient levels, with the exception of Mg.

Another relevant finding of this study is the increase of pH, which was significant in the high intensity fires. Through leaching, the Haplic Luvisol will likely have a much higher pH, which can directly affect pH sensitive vegetation (e.g., native rare species such as *Quercus frainetto* Ten.).

This study indicates that there are potential negative effects on soil fertility based on the decrease of potassium in the experiment. Potassium is a key nutrient for the ion transport within vegetation. Any loss of this from the soil would have major influences on the agricultural sector of the Hungarian economy. With an increased forest fire risk across Europe, from the 2041–2070 A1B emission scenario [61], nutrient rich soil, such as Haplic Luvisol, will be adversely affected by losses in K. As such, this study provides a reference point for further investigation into the effect of fire intensity on Haplic Luvisol and for any soil type that could be subject to burning. To enable stronger conclusions to be drawn in future investigations, we recommend conducting a larger scale of experimental burning, to follow burned soils over a recovery period and to evaluate impacts on productivity. Nevertheless, we believe our findings provide useful evidence for Haplic Luvisol changes under fire disturbance, while also supporting the maintaining of the current Hungarian fire prevention policy.

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Appendix A

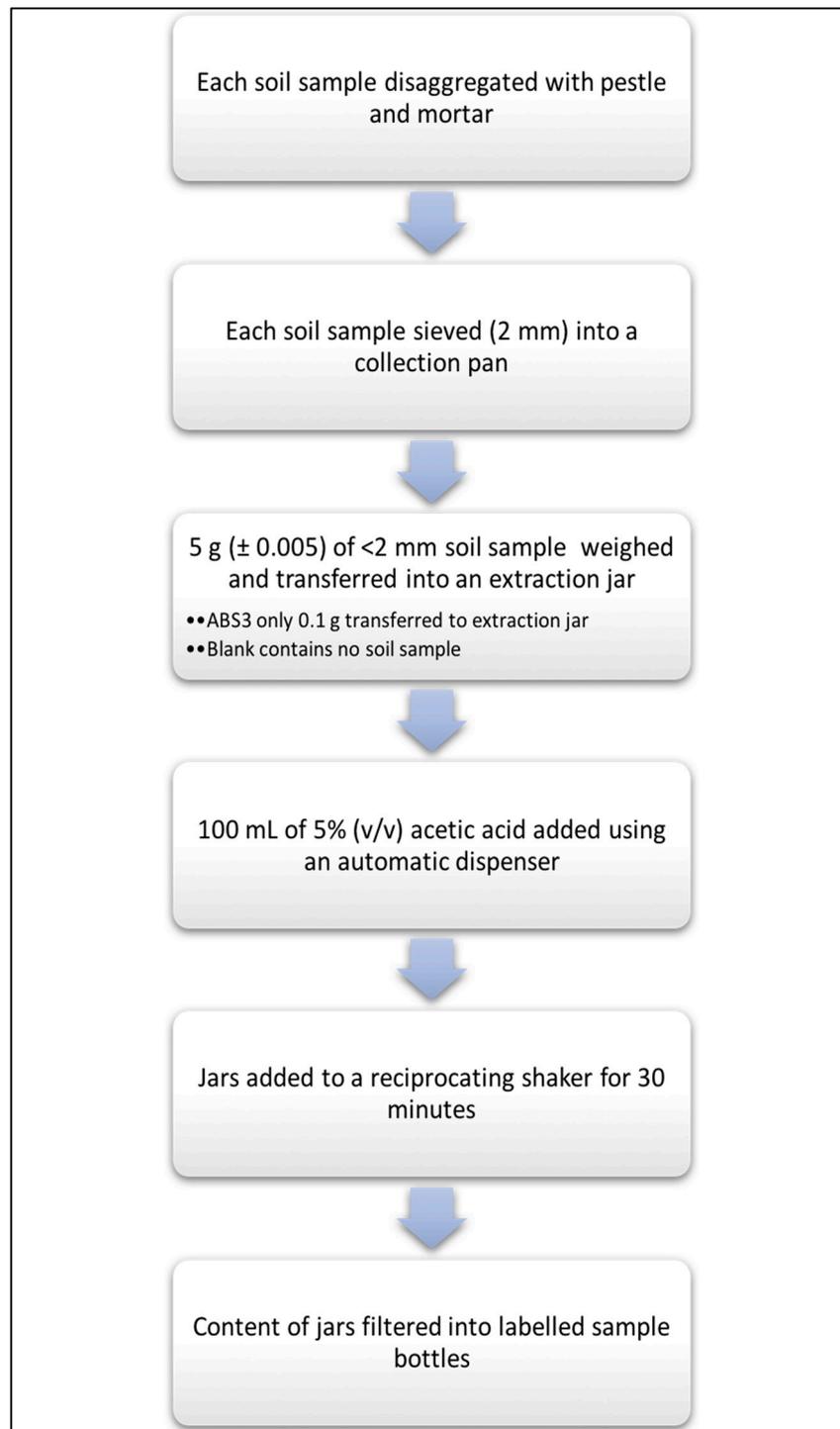


Figure A1. Method used to prepare soil samples for AAS and UV-spectroscopy analysis for plant available concentration.

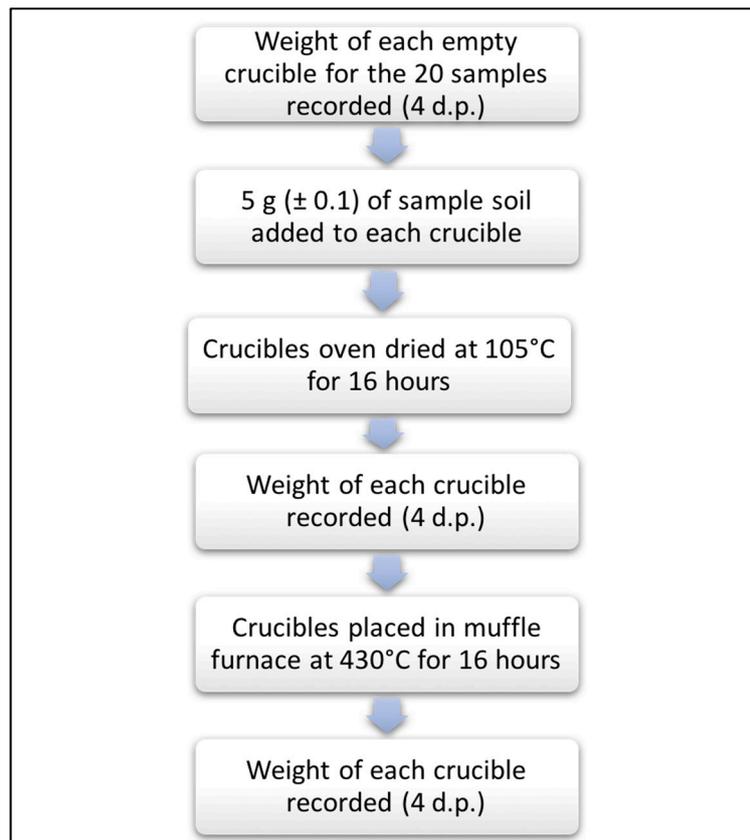


Figure A2. Method used for organic matter (OM) and C analysis of all samples.

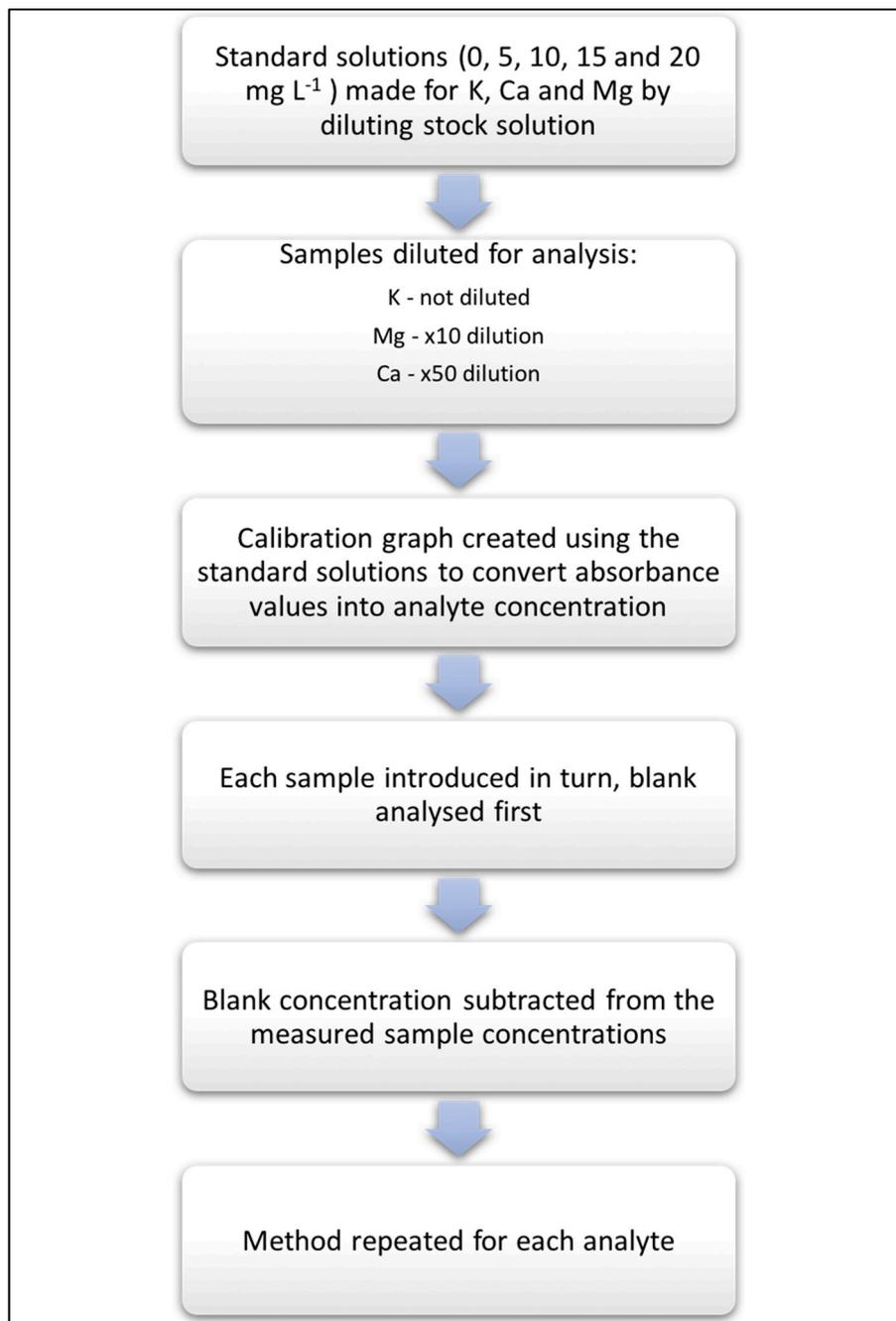


Figure A3. Method used for Ca, K and Mg analysis of all samples.

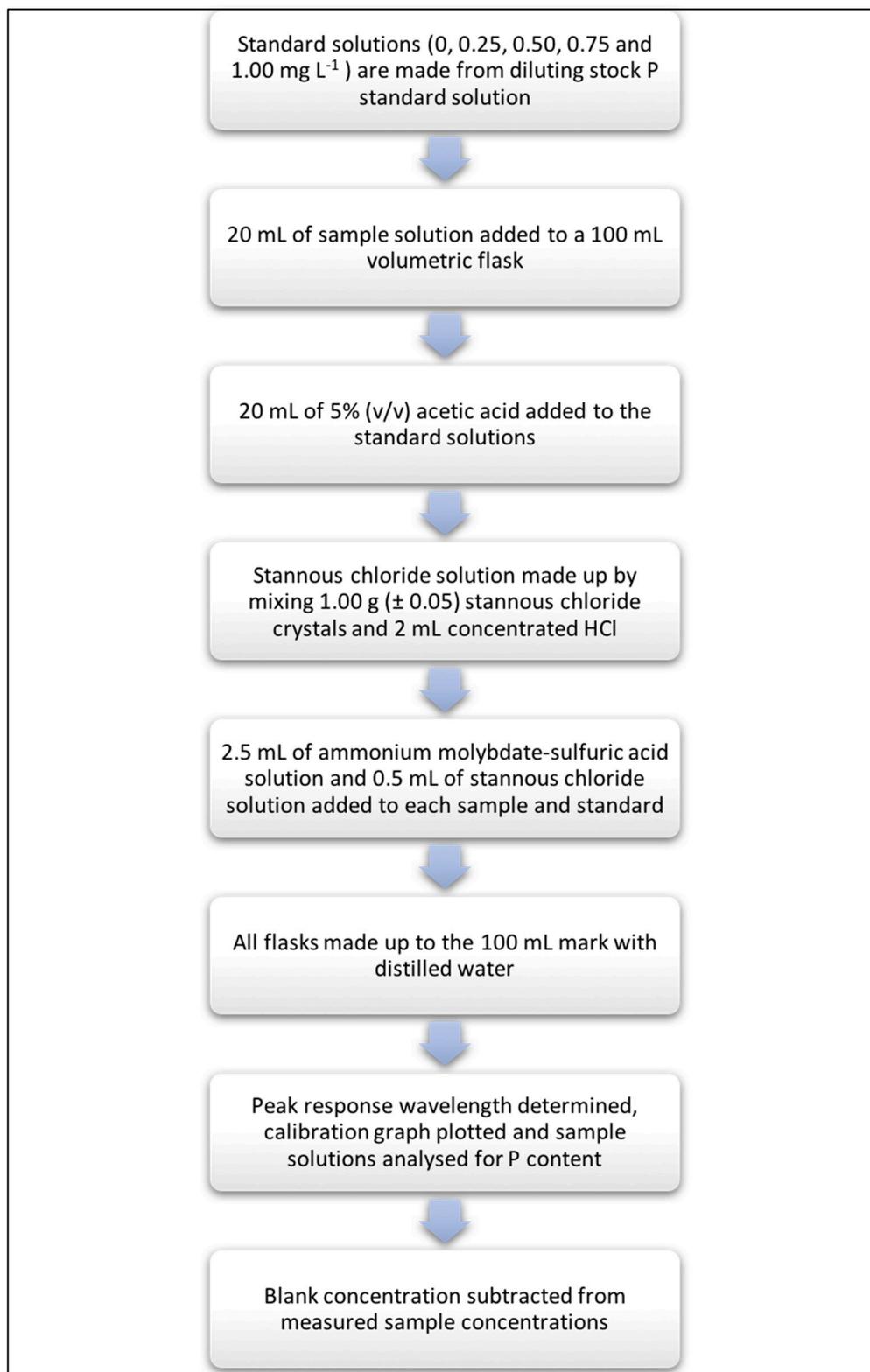


Figure A4. Methods used for P analysis of all samples.

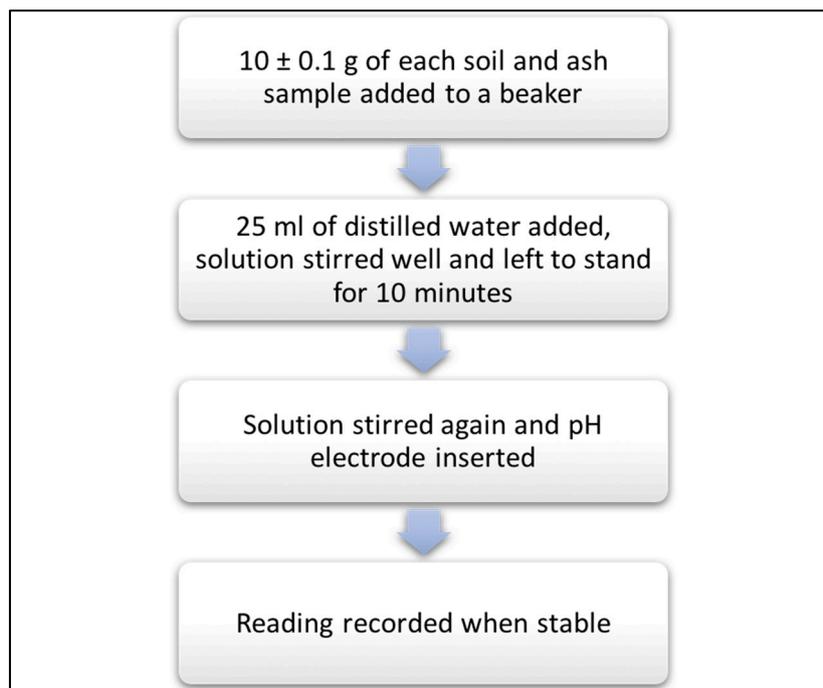


Figure A5. Method used for soil and ash pH analysis.

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