Title: Decadal effect of post-fire management treatments on soil carbon and nutrient concentrations in a burnt Mediterranean forest

Raquel Juan-Ovejero[1], Carlos R. Molinas-González[1,2], Alexandro B. Leverkus[1], Francisco J. Martín Peinado[3] and Jorge Castro[1]

[1]Departamento de Ecología, Universidad de Granada, 18071 Granada, Spain

[2]Instituto de Investigación Biológica del Paraguay (IIBP), 1425 Asunción, Paraguay

[3]Departamento de Edafología y Química Agrícola, Universidad de Granada, 18071 Granada, Spain

**Corresponding author:*
Juan-Ovejero, R.
Departamento de Ecología, Universidad de Granada
18071 Granada, Spain
Telephone: (+34)958241000; e-mail address: rjuan@ugr.es

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Highlights

1. Salvage logging reduced soil carbon and nutrient concentrations compared to a treatment with burnt trunks scattered over the ground.

2. The decrease was consistent at two elevations.

3. The effects of post-fire salvage logging on soil nutrient concentrations persist in a medium- to long-term perspective, albeit with a moderate magnitude.

Abstract

Wildfires and post-fire burnt-wood management treatments disturb the soils of forest ecosystems. However, little attention has been paid to the impact of these compound disturbances from a medium- to long-term perspective. In this study, we compared the decadal effect on soil carbon and nutrient concentrations (i.e. C, N, K and P) of two post-fire burnt wood treatments that differed in management intensity. We established two blocks differing in elevation, each including three replicates (ca. 3 ha) of each of two treatments: salvage logging (SL), a treatment that emulated a conventional salvage logging (although logs of dead wood were stacked within-plots in piles covering < 5% of the area), and a treatment where 90% of the burnt trees were manually cut but all biomass was haphazardly spread over the ground (partial cut, PC). Soil carbon and nutrient concentrations were compared across treatments, across the bare soil of both treatments, and in areas of bare soil versus areas below burnt trunks within the PC treatment. All analyzed soil chemical properties differed between elevation blocks. Moreover, C, K and P concentrations were higher in the PC treatment than in the SL treatment, although effect sizes were small. Similarly, C and P were higher in the bare soil of the PC treatment than in the bare soil of the SL treatment. However, the soil away from logs and the soil underneath logs did not show significant differences for C, N, K and P concentrations within the PC treatment, suggesting that scattered dead wood originated a higher log cover that physically protects the soil and enhances nutrient availability. Our findings indicate that, a decade after wildfire and treatment implementation, salvage logging produced lower soil carbon and nutrient concentrations than another management treatment which left all wood scattered over the ground. Studying the long-lasting impacts of post-fire management strategies is essential to propose suitable management approaches that contribute to recover soil nutrient availability.

Keywords: dead wood, post-fire strategy, salvage logging, soil properties, wildfire

1. Introduction

Wildfires alter biogeochemical cycles through combustion, subsequent nutrient leaching, the interruption of primary production, and the initiation of decomposition of remaining dead biomass (Pellegrini et al., 2018). Despite an immediate pulse in nutrient supply through the deposition of ashes, nutrient pools are reduced in the mid-to long term due to severe changes in mineralization and decomposition rates that lead to nutrient losses (Certini, 2005). However, large nutrient pools remain inside the burnt wood, whose gradual decomposition fertilizes the soil for decades (Marañón-Jiménez and Castro, 2013). Such fertilization may be critical for the productivity of early successional vegetation in nutrient-limited ecosystems such as many of Mediterranean type (Carreira et al., 2004; Taboada et al., 2017). However, the extraction of the burnt wood is among the most common human responses to wildfires (Müller et al., 2019; Castro 2021), which produces the question of whether management may be reducing the concentrations of soil carbon and nutrients in the order of decades after a fire.

Salvage logging generally encompasses massive tree cutting, the use of heavy machinery to extract dead-wood from the burned areas, and the additional mastication or burning of the woody debris (Lindenmayer et al., 2008). This practice is commonly justified by the recovery of timber value as well as the reduction of woody material to decrease fire risk and pest outbreaks (Leverkus et al., 2021). However, there is a great deal of debate between conservationists, policy-makers and forest managers about whether salvage logging is an appropriate post-fire management strategy (Lindenmayer et al., 2017; Castro 2021). Despite it being used worldwide, aggressive logging operations and dead-wood removal may negatively affect biodiversity (Thorn et al., 2018), lessen seedling establishment and tree regeneration (Castro et al., 2011), affect carbon dynamics (Serra-Ortiz et al., 2011; Powers et al., 2013), and reduce the recuperation of soil fauna (Molinas-González et al., 2019) and microbial communities (Pereg et al., 2018). Moreover, intense post-fire interventions may originate additional disturbances in forests by influencing key ecosystem functions and services such as

carbon sequestration, nutrient cycling and water regulation (Lindenmayer and Noss, 2006; Leverkus et al., 2018a, 2020).

The dead wood that remains spread over the ground is an important biological legacy (Franklin et al., 2000) that constitutes the largest portion of post-fire forest biomass. It plays a crucial role in providing organic matter resources through its decomposition and reducing abiotic stress for plants (Castro, 2021). Dead wood legacies serve as a hotspot of macro- and micro-nutrients, thereby enhancing soil fertility and nutrient cycling (Marañón-Jiménez et al., 2013; Donato, 2016). Moreover, burnt wood improves microclimatic suitability for seedling establishment and tree regeneration by decreasing excessive solar radiation and soil moisture losses (Castro et al. 2011; Marzano et al., 2013; Taboada et al., 2017; Marcolin et al., 2019). Altogether, dead wood may positively influence the recovery of post-disturbed forest ecosystems and buffer the impact of wildfires and post-fire perturbations (Lindenmayer et al., 2019).

The compounded effect of wildfires and post-fire management treatments may originate long-lasting disturbances in forests and affect the resilience of burnt ecosystems (Buma and Wessman, 2011; Leverkus et al., 2018b; Kleinman et al., 2019). Importantly, the effect of these disturbances could be longer-lasting in the belowground environment than above-ground because the recovery of soil properties and functions may be more dependent on the gradual input of decomposing dead wood (Bowd et al., 2019, 2021). Several studies have addressed the short-term effects of salvage logging on the physical and chemical properties of forests soils (e.g. Spanos et al., 2005; Poirier et al., 2014; García-Orenes et al., 2017). However, only considering short-term data precludes portraying the dynamics of forest soils after natural and anthropogenic disturbances (Seedre et al., 2011), and our fundamental understanding of the influence of these compounded perturbations on the below-ground environment in the medium- to long-term remains poor (Leverkus et al., 2018a).

In this study we aim to assess, ten years after a wildfire, the effect on soil carbon and nutrient concentrations of post-fire salvage logging in comparison with another

treatment that scattered all burnt wood over the ground in a Mediterranean coniferous forest. For that, we established an experiment with two blocks located at different elevation, each containing three plots of two post-fire burnt-wood management treatments. One of the treatments emulated salvage logging, a post-fire management strategy that creates a simplified habitat devoid of trees and with a high soil disturbance through heavy-machinery operations and woody debris mastication. The other treatment, partial cut, consisted in the felling of most trees with chainsaws but leaving them haphazardly spread on the ground without further intervention. We used this experimental setting to analyze the medium-term effect of post-fire dead-wood management on soil properties across treatments, across a microhabitat that was abundant in both treatments (characterized by bare soil), and across two distinctive microhabitats that abounded within the treatment that retained all wood over the ground (bare soil and soil under logs). Our hypotheses were that: 1) soils in the partial cut treatment would contain higher carbon and nutrient concentrations than in salvage logging, 2) under similar microhabitat conditions (i.e. soil devoid of logs), soil carbon and nutrient concentrations would be lower in the salvage logging treatment, and 3) in the partial cut treatment, carbon and nutrient concentrations would be higher in the soil under logs than away from logs because dead wood would create nutrient hotspots.

2. Materials and Methods

2.1. Study area and sampling design

The study site is located in the Sierra Nevada Natural and National Park (SE Spain; 36º 57’ 12’’ N; 3º 29’ 36’’ W), where in September 2005 the Lanjarón wildfire burned approximately 3400 ha, of which some 1300 ha consisted of reforested pine stands. Reforestations in the area were done ca. 50 years ago to reestablish tree cover on long-deforested hillslopes, using terraces made with bulldozers, previously a common reforestation practice on hillsides in Spain. Each terrace stairstep is composed of a steep cutslope (approx. 90 cm high), and the nearly flat area of the terrace (“terrace” hereafter)

of approx. 3 m in width. The fire was high in intensity, affecting all the leaves, twigs and litter as well as charring the bark of the trunks (Marañón-Jiménez et al., 2013). The climate is Mediterranean, with hot and dry summers and most rainfall occurring in spring and autumn. Snow usually persists from November to March above 2000 m a.s.l.

Six months after the wildfire, we established two blocks in two distinct locations following a generalized randomized block design (Fig. 1). The two blocks were dominated by 40-60 year-old pine stands, had similar features concerning lithology (mica schist), soil type (dominance of leptic Phaeozem and inclusions of eutric Cambisol) and aspect (SW) but differed in elevation: one was located at 1477 m a.s.l. (low block) and the other at 2053 m a.s.l (high block). They consequently represent two contrasting conditions in terms of dominant pine species and environmental factors (Table 1), providing the opportunity for testing the studied hypotheses across two elevational levels.

The manipulation of burnt wood was performed with two different treatments at the two selected blocks (same as in Molinas-González et al., 2019). At each block, we established 3 plots of each of the following treatments: 1) partial cut (PC), which encompassed the manual felling of approximately 90% of the burnt trees, with the largest branches lopped off and the trunks cut in 2-3 pieces. The trees and the branches were haphazardly spread on the ground without chopping, and the remaining 10% of the burnt trees were left standing but collapsed quickly until 100% had fallen after 5.5 years. The initial habitat structure in this treatment was characterized by logs and branches covering 45% of the ground, and the wood lost 23% of the initial density 10 years after fire (Molinas-González et al., 2017). d 2) salvage logging (SL), where all the burnt trunks were cut in 3 m long pieces, cleaned of branches with manually operated chainsaws, and manually piled in groups of 10-15. The remaining woody debris was masticated in pieces of approximately 2-5 cm of diameter with the mechanical chopper of a crawler tractor, and the slash was spread on the ground. This is a common post-fire management procedure conducted by the local forest service, and is followed by the removal of the logs with a log-forwarder. In the Lanjarón experiment, the forest service had also planned

200 the extraction of the burnt trunks, but this step was finally canceled due to difficulties in
201 precisely operating the log-forwarder within the spatial placement of the blocks. The
202 habitat structure in SL was therefore characterized by an open landscape with groups of
203 stacked logs covering less than 5% of the whole post-fire treatment area. Each of the
204 three plots that constituted the replicate units of each treatment in each block had a size
205 of ca. 3 ha (Fig. 1). Subsequently, in each plot of the PC treatment we selected two soil
206 sampling environments that represented the microhabitats that were most abundant in
207 this treatment regarding burnt tree distribution on the ground: one with dead wood spread
208 on the ground (PC/under logs microhabitat) and another one without logs (PC/bare soil
209 microhabitat). In the plots of the SL treatment we only considered the bare soil
210 microhabitat (SL/bare soil microhabitat). In SL, the soil samples were collected far away
211 (at least 3 m) from the piles of trunks to avoid potential effects of the presence of logs.
212 Note that this treatment (SL) seeks to simulate a complete salvage logging where the
213 logs would be removed from site, and thus our microhabitat of interest is bare soil. Soil
214 samples were collected in all cases in the flat area of the terraces.
215
216 **2.2. Soil sampling and chemical analyses**
217 We collected soil samples to measure soil carbon and nutrient concentrations in spring
218 2016 (10.5 years after the wildfire). Twelve soil samples were taken at random locations
219 in each combination of block, treatment replicate and microhabitat (*n* = 216 samples in
220 total; Fig. 1). Soil cores were extracted using soil augers (10 cm Ø x 12-15 cm depth)
221 and samples were kept in plastic bags. In the lab, soil samples were air-dried and sieved
222 with a 2 mm mesh. We recorded the coordinates of all sampling points with a GPS, and
223 the elevation of each point was calculated with a Digital Elevation Model (DEM; 5 m grid
224 size) of the area obtained from the Spanish National Geographic Institute
225 (https://centrodedescargas.cnig.es).
226 Total carbon and nitrogen were measured with an elemental analyzer (LECO®
227 TruSpec CN, St. Joseph, MI, USA), and results were expressed as percentages.

228 Available inorganic phosphorus was extracted with $NaHCO_3$ according to Olsen and
229 Sommers (1982) and data were expressed as ppm. Potassium concentration was
230 determined by cation displacement with ammonium acetate according to the
231 methodology of the Soil Conservation Service (1972) and measured by atomic
232 absorption spectroscopy using a spectrometer (VARIAN® SpectrAA 220FS, Palo Alto,
233 California, USA), with results expressed as $cmol_+ kg^{-1}$.
234

235 **2.3. Statistical analyses**

236 We used linear mixed models with the 'lme4' package (Bates et al., 2015) to analyze the
237 effects of block and dead-wood treatment (Hypotheses 1 and 2) and of block and
238 microhabitat (Hypothesis 3) on the different measured soil properties (i.e. C, N, K and
239 P). We carried out model simplification to select the best-fitting model for each response
240 variable. The initial model for each response variable was built by adding block and dead-
241 wood treatment (Hypotheses 1 and 2) or block and microhabitat (Hypothesis 3) and their
242 interactions as fixed effects, and plot (i.e., treatment replicate) as a random effect to
243 account for the spatial nonindependence of the samples. We added the elevation within
244 block as a covariate in all models to control for the variability in elevation between
245 sampling points within each block (which was up to ~150 m). When performing the model
246 simplification, we first eliminated the interactions and, thereafter, each one of the fixed
247 factors, and assessed the significance of each term ($p < 0.05$) by using maximum
248 likelihood ratio tests (ML). Best-fitting models –i.e., those with all significant effects
249 included– were graphically analyzed for non-constant error variance and normality of the
250 residuals.

251 To evaluate the magnitude of post-fire treatment effects, standardized effect size
252 measures of blocks and dead-wood treatments of the best-fitting models were calculated
253 with Cohen's d tests using the 'emmeans' R package (Lenth, 2021). For this test, the
254 scales of the magnitude of the effect sizes follow this convention: $0.00 < h < 0.50$: "small

effect size"; 0.50 ≤ h ≤ 0.80: "medium effect size" and h > 0.80: "large effect size" (Cohen, 1988).

Principal Component Analysis (PCA) was performed with the 'vegan' package (Oksanen et al., 2019) to determine relationships between nutrient concentrations (C, N, K and P) and elevations across blocks and microhabitats. For K and P, 0.0001 units (i.e. below detection limits) were added to all values to avoid zero values in the data.

All analyses were performed in R (R.3.6.2., R Core Team).

3. Results

C, K and P were significantly affected by block and dead-wood treatment, whereas N was only influenced by block (Hypothesis 1). There was no significant effect of the elevation-within-block covariate for any response variable (Table 2). The concentrations of C and P were greater in the high block than in the low block (Table 3; Figs. 2a,d), with an effect size being large for the former (0.916) and medium for the latter (0.712). Moreover, C and P were greater in the partial cut treatment than in salvage logging (Table 3; Figs. 2a,d), with small effect sizes of 0.447 and 0.495, respectively. K concentration was greater in the partial cut treatment than in the salvage logging treatment (Table 3; Fig. 2c), but differences were only significant at the low plot and the effect size was small with a value of 0.337. N concentration was greater in the high block than in the low block (Table 3; Fig. 2b) and the effect size was large with a value of 1.41, but no significant differences were found between dead-wood treatments.

When assessing for differences between the bare soil microhabitat across the two dead-wood treatments (Hypothesis 2), block and dead-wood treatment produced a significant effect on C and P concentrations, and only block had a significant effect on N and K. Additionally, similar to Hypothesis 1, no response variable was influenced by the elevation-within-block covariate (Table 2). C and P concentrations were greater in the high block than in the low block (Table 3; Figs. 3a,d), with large effect sizes of 0.893 and 0.790, respectively, and the bare soil of the PC treatment had greater C and P levels

than the bare soil of the SL treatment (Table 3; Figs. 3a,d), with small effect sizes of 0.414 and 0.404, respectively. Moreover, N concentration was greater in the high block than in the low block (Table 3; Fig.3b) with a large effect size of 1.42. However, the opposite pattern was observed for K (Table 3; Fig.3c) and the observed effect size for this difference was small, with a value of 0.451.

The comparison of microhabitats in the PC treatment (Hypothesis 3) showed that all response variables were only influenced by block (Table 2). C, N and P concentrations were greater in the high block than in the low block (Table 3; Figs. 4a,b,d) and showed effect sizes of 0.906, 1.380 and 0.670, respectively. Contrarily, K concentration was greater in the low block than in the high block (Table 3; Figs. 4c), with a medium effect size of 0.539.

The PCA indicated that soil C and nutrient concentrations of the sampling points of the high block were substantially different from those of the low block (Fig. 5). This variation was mainly explained by the first two PCA axes (PC1 explained 49.24% of the total variance, and PC2 explained 23.60%), and the output showed that C, N and elevation were strongly related in the sampling points of the high block. Moreover, at both blocks, the centroid of SL/bare soil was located at the lowest position in the output, followed by the centroid of PC/bare soil, and the centroid of PC/under logs was located in the highest position.

4. Discussion

Our findings indicate that, ten years after the implementation of dead-wood management, a treatment emulating an intense intervention such as salvage logging reduced soil carbon and nutrient concentrations in comparison with another treatment that retained all burnt wood scattered over the ground. However, soil carbon and nutrient concentrations underneath logs and away from logs did not differ from each other within the partial cut treatment, suggesting that the beneficial effect of this less intense management treatment also applied to microhabitats that were not directly underneath

311 a log. This effect may be related to both carbon and nutrient supply from the wood
312 through decomposition, and to a higher nutrient retention resulting from increased soil
313 protection provided by the felled trunks and branches. In short, the results support that
314 that not using heavy machinery and leaving the burnt wood over the soil surface can
315 benefit soil fertility.

316 The partial cut treatment enhanced the levels of C, K and P compared to salvage
317 logging 10 years after fire (Hypothesis 1). Similarly, C and P concentrations were
318 significantly higher under the bare soil in PC when compared to the bare soil in SL
319 (Hypothesis 2). In concordance with our results, studies addressing the effects of salvage
320 logging on soils within time frames longer than 10 years showed a broad consensus
321 about the negative consequences of this post-fire treatment for the capacity of soils to
322 store carbon (Brais et al., 2000; Johnson et al., 2004; Powers et al., 2013; Keith et al.,
323 2014; Wilson et al., 2021). Moreover, in our study, K was depleted after dead-wood
324 removal in the low block (Hypothesis 1), agreeing with previous studies which indicated
325 that salvage logging effects on K concentrations could persist for various decades and
326 stand rotations (Brais et al., 2000; Kishchuk et al., 2014; Bowd et al., 2019). The drivers
327 of P concentrations are less clear following wildfires and post-fire management
328 treatments. P availability did not differ between different post-fire management
329 treatments in one study also conducted at the decadal scale (Kishchuk et al., 2014), but
330 results observed across a forest chronosequence agreed with our findings by indicating
331 that P concentrations may be severely reduced by aggressive post-fire treatment
332 implementations in the long-term (Bowd et al., 2019). In our study, we found significant
333 differences for P between dead-wood treatments, and it should be noted that, although
334 the effect size was small (0.495), the magnitude of the differences was relevant (Table
335 3). Specifically, P exhibited mean values of 1.17 ± 0.13 ppm and of 2.12 ± 0.20 ppm in
336 the low and high blocks of the SL treatment, respectively, whereas in the low and high
337 blocks of the PC treatment, mean values were 1.82 ± 0.13 ppm and of 2.97 ± 0.25 ppm,
338 respectively. These values are considered very low, even taking into account that the P

339 extraction method used in this study (Olsen) may not have extracted part of the labile
340 fractions that other methods do extract (e.g. Bray). However, when comparing P
341 concentrations measured by Olsen method in relation to other methods (Wuenscher et al.,
342 2015), we can consider that our values are in the range of a strong P limitation (i.e. < 10
343 ppm; Syers et al., 2008), and therefore any increase in this element might be crucial at
344 ecosystem level. Phosphorus limitation is, in fact, a critical constraint in Mediterranean-
345 type ecosystems (Sardans et al., 2004, 2006) and can act as a structuring force in plant
346 communities (Richardson et al., 2004). Altogether, dead wood scattered on the ground
347 represented a key nutrient reservoir that avoided decreases in soil carbon and nutrient
348 concentrations in the medium-term. Broadening the range of studied variables could give
349 a more precise view of the complex network of processes occurring in the soil matrix.

350 Contrary to the above-mentioned elements, nitrogen levels neither differed
351 between dead-wood treatments nor between the bare-soil microhabitat within the PC
352 treatment. In agreement with this, other studies documented that soil nitrogen
353 concentration was replenished after wildfire and post-fire treatment implementations
354 because the nitrogen inputs provided by legumes compensated for the initial losses
355 caused by disturbances (Brais et al., 2000; Johnson et al., 2004, 2005). Our results may
356 be explained by the presence of N-fixing shrubby species such as *Adenocarpus*
357 *decorticans* Boiss., *Ulex parviflorus* Pourr. and *Genista versicolor* Boiss., which
358 regenerated on the whole burned area and were particularly abundant two years after
359 treatment implementation (Leverkus et al., 2014). Likewise, *Ceanothus velutinus* Dougl.
360 is another pioneer species that was able to recover close-to pre-fire nitrogen levels in a
361 similar Mediterranean-type forest ecosystem at the scale of decades, buffering the
362 impact of post-fire management on this element (Johnson et al., 2005).

363 We did not find support for hypothesis 3, since there were no significant
364 differences for any element across the microhabitats covered by logs and devoid of logs
365 in the PC. Similarly, in a five-year post-fire study (Gómez-Sánchez et al., 2019; Lucas-
366 Borja et al., 2020), soil organic matter and nutrient concentrations were positively

influenced by burnt-wood treatments that left biomass on the ground and used non-heavy mechanical operations (i.e. log erosion barriers and contour-felled log debris). These results support our findings by showing that post-fire management that massively retains wood can be beneficial for the recovery and/or maintenance of the soil fertility. However, other short-term sampling designs and/or small spatial sampling scales have rendered scant or null effects of post-fire salvage logging on soil nutrient availability (Ginzburg and Steinberg, 2012; Poirier et al., 2014, Parro et al., 2019), in contrast to the long-term effect reported in this and other studies (Brais et al., 2000; Kishchuk et al., 2014; Bowd et al., 2019). Thus, our results shed light on the need for an appropriate management in order not to compromise the nutrient storage capacity of burnt forest ecosystems in the long-term.

Finally, since there were no interactive effects between block and dead-wood management treatment on any soil chemical property, the significant differences and large effect sizes in soil C and nutrient concentrations between elevation blocks may be merely attributed to the different features of the two selected blocks. Lower temperatures and greater rainfall at higher elevation limit soil development by reducing organic matter decomposition (i.e. higher C/N ratio), creating lower base saturation (i.e. lower K concentrations), higher concentrations of available P and more acidic pH (Sánchez-Marañón et al., 1996). Therefore, the presence of dead wood had a consistent positive effect on soil carbon and nutrient concentrations irrespective of the elevational gradient.

5. Conclusions

This study demonstrates that the management treatment that left all dead wood scattered over the ground was more convenient than salvage logging for enhancing soil carbon and nutrient concentrations ten years after fire. Although the size of the observed effects between dead-wood strategies was small, it is important to note that any increase in the availability of very limiting nutrients (i.e. phosphorus) may positively affect the plant community. However, soil carbon and nutrient concentrations underneath logs and away

from logs were not statistically different at the microhabitat scale. Taking these findings together, our results support that the long-term retention of dead wood may constitute a resource that releases nutrients over the long run and physically protects the soil, ultimately promoting the recovery of post-disturbed forests. Further research on the spatio-temporal dynamics of dead wood legacies could enhance the management of forests after compounded disturbances (Lindenmayer et al., 2019; Leverkus et al., 2021). Therefore, we need a better understanding of the state of the soil with well-replicated data in order to better predict the effectiveness of long-term management actions on the whole forest ecosystem.

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Table 1. Main characteristics of the two studied blocks across the elevational gradient.

	Block	
	Low	**High**
Coordinates[a]	36º 57' 12" N; 3º 29' 36" W	36º 58' 6" N; 3º 28' 49" W
Area (ha)	17.7	31.7
Slope (%)	25-30	35
Elevation[a]	1477	2053
Dominant tree species	*Pinus nigra+Pinus pinaster*	*Pinus sylvestris*
Climatic features		
Mean daily minimum temperature (ºC)[b]	6.8 ± 0.2	3.4 ± 0.2
Mean daily maximum temperature (ºC)[b]	17.1 ± 0.2	13.4 ± 0.2
Mean annual precipitation (mm)[b]	536 ± 41	630 ± 42
Soil parameters		
Bulk density (g cm-3)[c]	1.25 ± 0.06	1.15 ± 0.06
Texture (%)[c]	Sandy loam	Sandy loam
Sand (0.05-2 mm)[c]	59.4 ± 2.4	69.0 ± 0.1
Coarse silt (0.02-0.05 mm)[c]	10.6 ± 0.8	9.7 ± 0.4
Fine silt (0.002-0.02 mm)[c]	15.2 ± 0.7	12.5 ± 0.4
Clay (<0.002 mm)[c]	14.8 ± 0.9	8.8 ± 0.3
pH[c]	7.27 ± 0.04	6.71 ± 0.08
Dasometric parameters		
Tree density (individuals ha-1)[c]	1477 ± 46	1051 ± 42
Diameter at breast height (cm)[c]	13.3 ± 0.2	10.7 ± 0.2
Tree height (m)[c]	6.3 ± 0.1	6.2 ± 0.1
Wood nutrients		
C (%)[c]	50.49 ± 0.08	50.63 ± 0.07
N (%)[c]	0.163 ± 0.004	0.189 ± 0.005
K (ppm)[c]	575 ± 36.75	359.33 ± 18.47
P (ppm)[c]	99.74 ± 5.17	91.49 ± 3.55
Vegetation cover		
	Salvage logging/Partial cut	**Salvage logging/Partial cut**
Total cover[d]	54.33 ± 1.59/68.98 ± 2.45	60.17 ± 2.45/76.81 ± 1.93
Woody cover[d]	22.83 ± 1.15/41.56 ± 2.73	54.69 ± 2.51/63.58 ± 1.40
Herbaceous cover[d]	31.50 ± 1.59/27.43 ± 2.28	5.47 ± 0.94/13.22 ± 1.50

[a] Measured at the centroid of each block.
[b] Data obtained from interporlated maps of Sierra Nevada (1981-2010) generated at the Centro Andaluz de Medio Ambiente (CEAMA).
[c] Data measured 6 months after the wildfire (autumn 2005) and obtained from Marañón-Jiménez et al. (2013).
[d] Data measured along transects two years after the fire (May-July 2007) and obtained from Leverkus et al. (2014).

Table 2. Model selection ($p < 0.05$) for each response variable (C, N, K and P) and for each tested hypothesis (Hypothesis 1, Hypothesis 2 and Hypothesis 3).

	Hypothesis 1[a]			Hypothesis 2[b]			Hypothesis 3[c]		
Response variable	**Fixed effects**	**Chi Square**	**P value**	**Fixed effects**	**Chi Square**	**P value**	**Fixed effects**	**Chi Square**	**P value**
C	Block x Treatment[1]	0.308	0.580	Block x Treatment[1]	0.373	0.542	Block x Microhabitat[1]	0.006	0.940
	Block	17.314	<0.001	Block	14.692	<0.001	Block	13.200	<0.001
	Treatment	10.136	0.001	Treatment	7.052	0.008	Microhabitat[3]	0.107	0.743
	Elevation within block[2]	0.726	0.394	Elevation within block[2]	1.484	0.223	Elevation within block[2]	0.019	0.889
N	Block x Treatment[1]	0.024	0.877	Block x Treatment[1]	0.038	0.845	Block x Microhabitat[1]	0.015	0.903
	Block	15.715	<0.001	Block	16.254	<0.001	Block	13.512	<0.001
	Treatment[3]	1.907	0.167	Treatment[3]	1.881	0.170	Microhabitat[2]	0.001	0.982
	Elevation within block[2]	0.130	0.719	Elevation within block[2]	1.105	0.293	Elevation within block[3]	1.245	0.265
K	Block x Treatment[1]	0.107	0.744	Block x Treatment[1]	0.168	0.682	Block x Microhabitat[1]	1.578	0.209
	Block	5.633	0.018	Block	5.883	0.015	Block	6.774	0.009
	Treatment	5.709	0.017	Treatment[3]	2.104	0.147	Microhabitat[3]	2.057	0.152
	Elevation within block[2]	0.309	0.578	Elevation within block[2]	0.163	0.686	Elevation within block[2]	0.432	0.511
P	Block x Treatment[1]	0.190	0.663	Block x Treatment[1]	0.107	0.744	Block x Microhabitat[1]	0.166	0.683
	Block	11.568	<0.001	Block	10.037	0.002	Block	9.577	0.002
	Treatment	11.123	<0.001	Treatment	6.178	0.013	Microhabitat[3]	3.045	0.081
	Elevation within block[2]	0.039	0.843	Elevation within block[2]	0.329	0.566	Elevation within block[2]	0.046	0.831

Degrees of freedom (d.f.) are 1 for each fixed effect or interaction. Numerical superscripts indicate the order in which non-significant terms were exluded from the final model.

[a] $n = 216$

[b] $n = 144$

[c] $n = 144$

Table 3: Mean values ± SE of C, N, K and P across dead-wood treatments and microhabitats at the low and high blocks.

	Low Block			High Block		
	Salvage Logging	Partial Cut		Salvage Logging	Partial Cut	
		Bare soil	Under logs		Bare soil	Under logs
C (%)	1.34 ± 0.06	1.52 ± 0.11	1.55 ± 0.10	1.75 ± 0.08	1.98 ± 0.06	2.00 ± 0.07
N (%)	0.086 ± 0.003	0.092 ± 0.006	0.091 ± 0.005	0.129 ± 0.006	0.135 ± 0.005	0.135 ± 0.006
K ($cmol_+kg^{-1}$)	0.13 ± 0.02	0.15 ± 0.02	0.20 ± 0.02	0.09 ± 0.00	0.11 ± 0.02	0.12 ± 0.02
P (ppm)	1.17 ± 0.13	1.63 ± 0.15	2.01 ± 0.22	2.12 ± 0.20	2.67 ± 0.31	3.28 ± 0.40

625 **Figure captions**

626 Figure 1: Location of the two blocks (i.e. Low Block and High Block) within Europe and
627 the Sierra Nevada National Park.

628

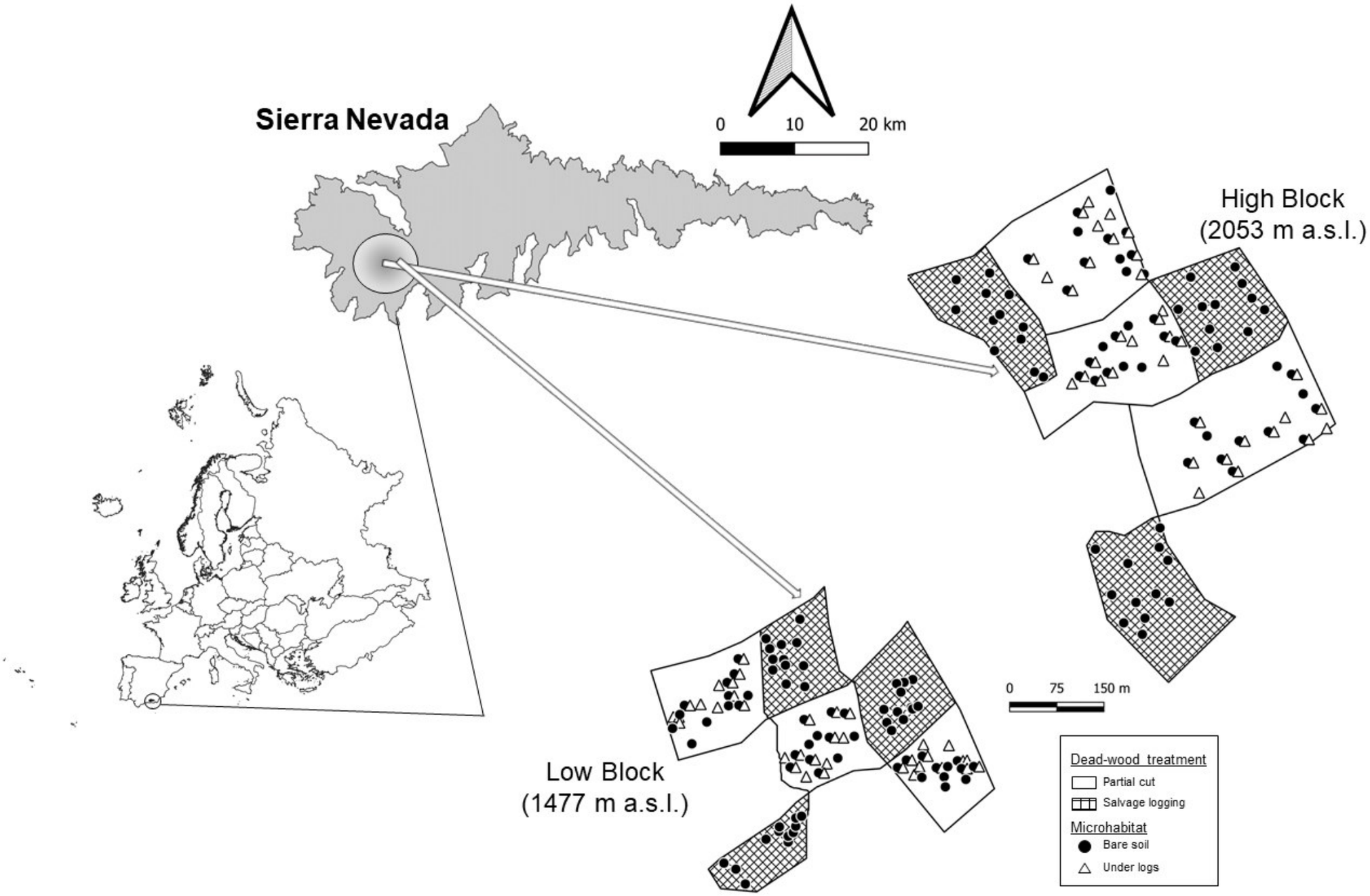
629 Figure 2: Boxplots with values of a) C (%), b) N (%), c) K ($cmol_{+}kg^{-1}$) and d) P (ppm)
630 within each block (Low Block and High Block) and for each dead-wood treatment (PC
631 and SL). All samples in the partial cut treatment were pooled together (i.e. both"bare soil"
632 and "under logs"). Each box spans the interquartile range, whiskers extend up to 1.5
633 times the interquartile range, the medians are represented as black lines and black dots
634 are outliers (*n* = 72 for PC within each block and *n* = 36 for SL within each block).

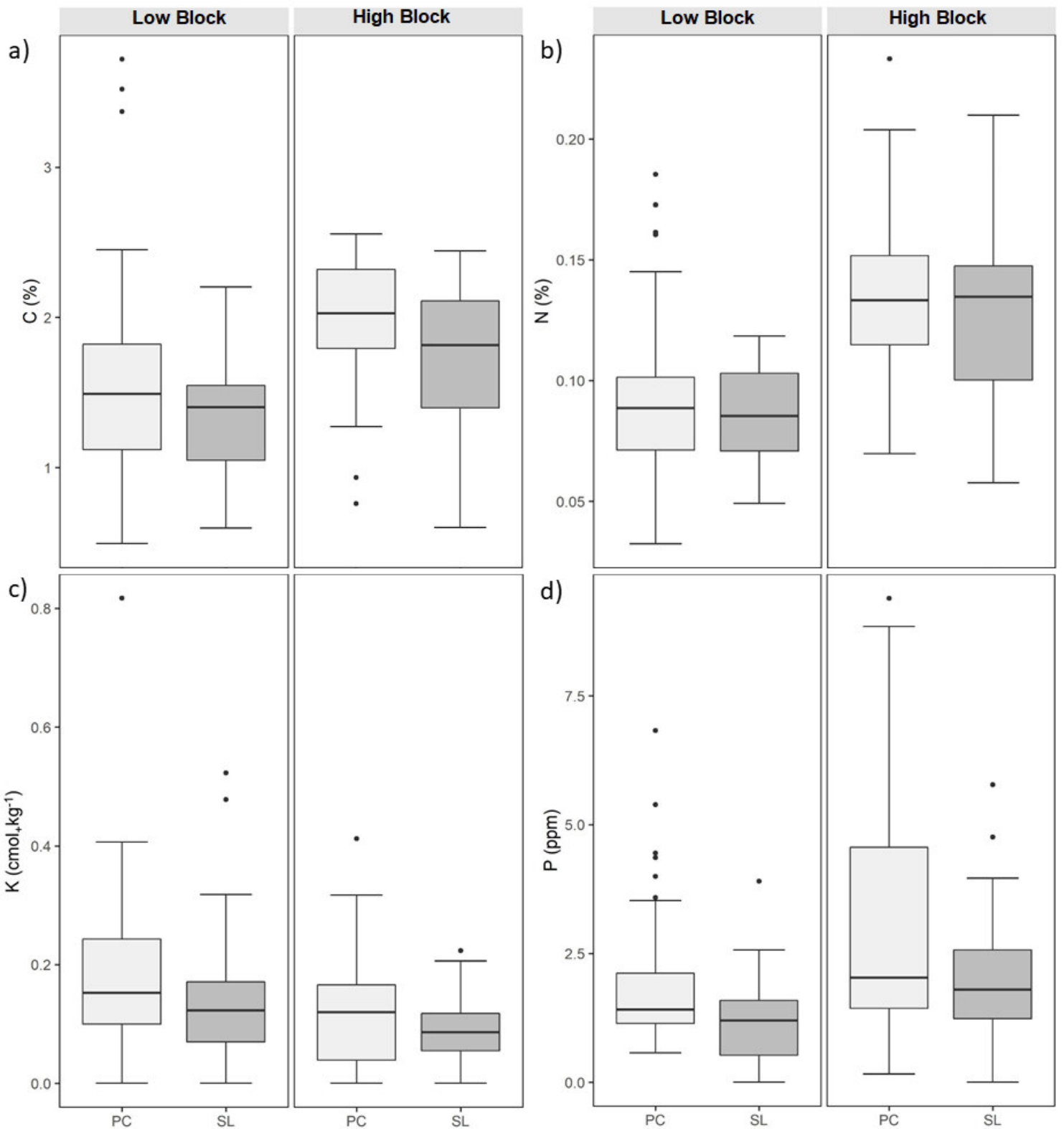
635
636 Figure 3: Boxplots with values of a) C (%), b) N (%), c) K ($cmol_{+}kg^{-1}$) and d) P (ppm)
637 within each block (Low Block and High Block) and for each dead-wood treatment within
638 the bare soil microhabitat (PC/bare soil and SL/bare soil). Each box spans the
639 interquartile range, whiskers extend up to 1.5 times the interquartile range, the medians
640 are represented as black lines and black dots are outliers (*n* = 36 for PC/bare soil within
641 each block and *n* = 36 for SL/bare soil within each block).

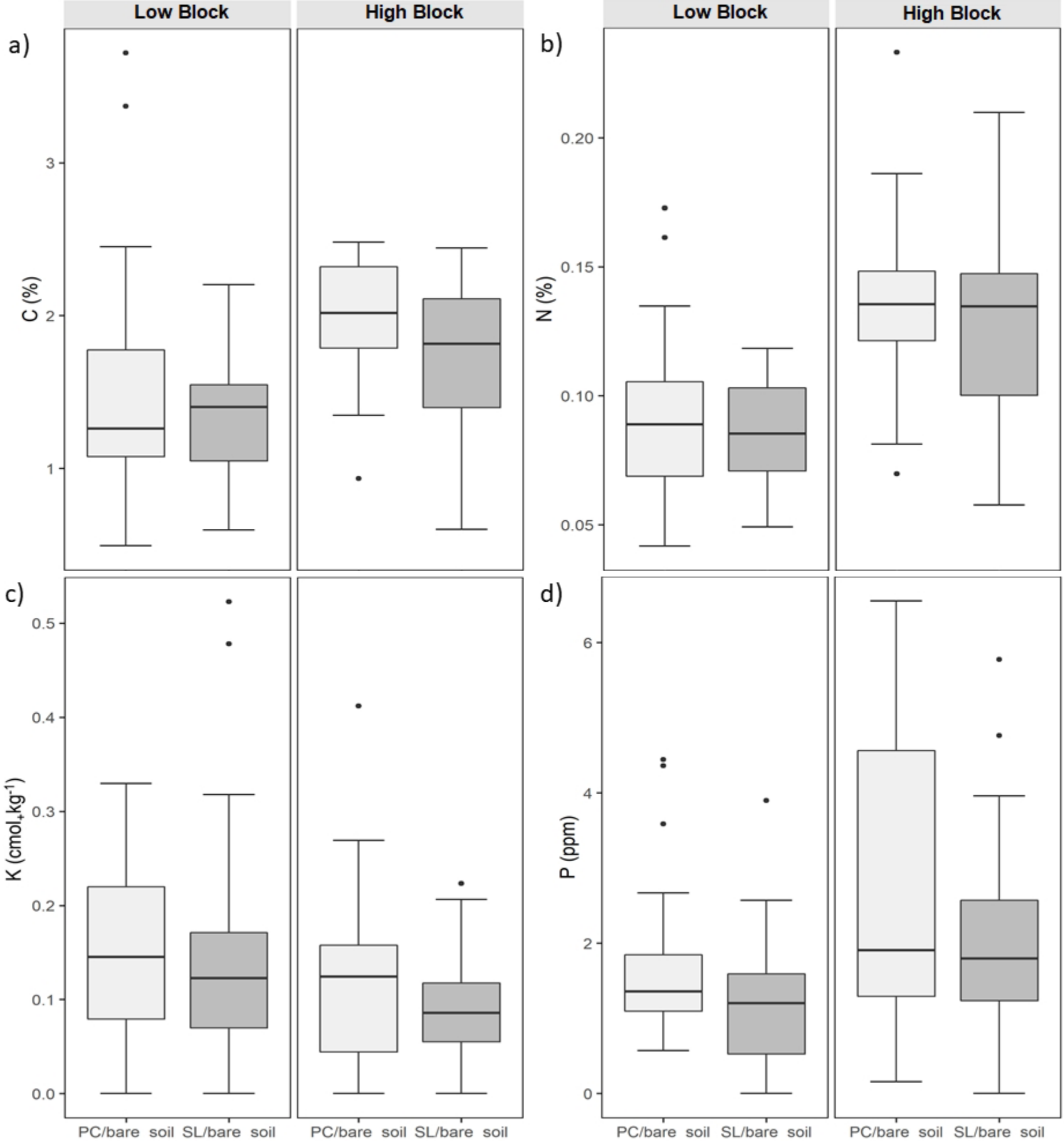
642
643 Figure 4: Boxplots with values of a) C (%), b) N (%), c) K ($cmol_{+}kg^{-1}$) and d) P (ppm)
644 within each block (Low Block and High Block) and for each microhabitat within the partial
645 cut treatment (PC/under logs and PC/bare soil). Each box spans the interquartile range,
646 whiskers extend up to 1.5 times the interquartile range, the medians are represented as
647 black lines and black dots are outliers (*n* = 36 for PC/bare soil within each block and *n* =
648 36 for PC/under logs within each block).

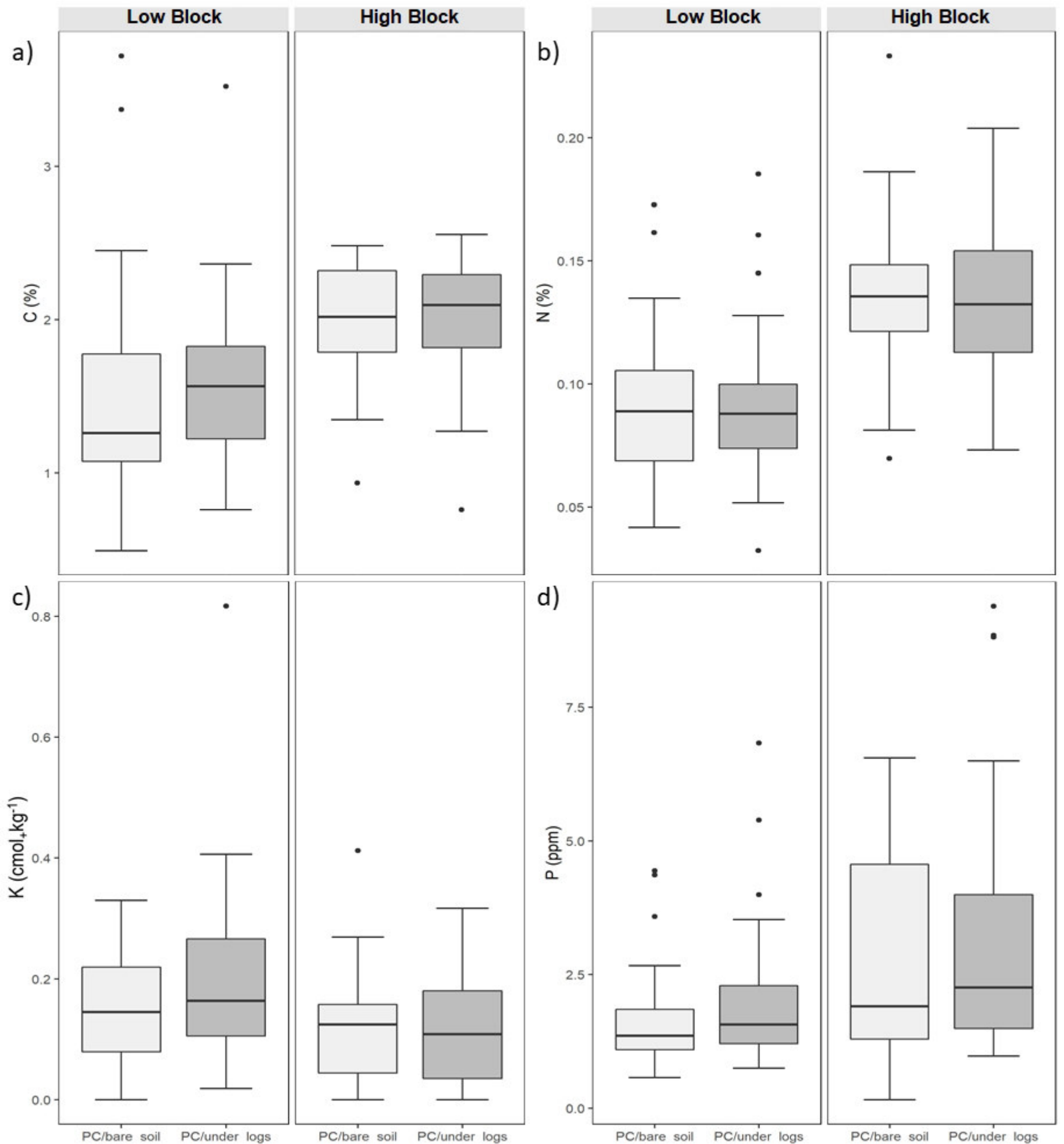
649
650 Figure 5: Principal Component Analysis (PCA) showing the changes along axes 1 and 2
651 for elevation and soil carbon and nutrient concentrations (C, N, K and P) across blocks
652 (open squares for Low Block and filled squares for High Block) and across microhabitats
653 of each dead-wood treatment (PC/bare soil in blue, PC/under logs in green and SL/bare

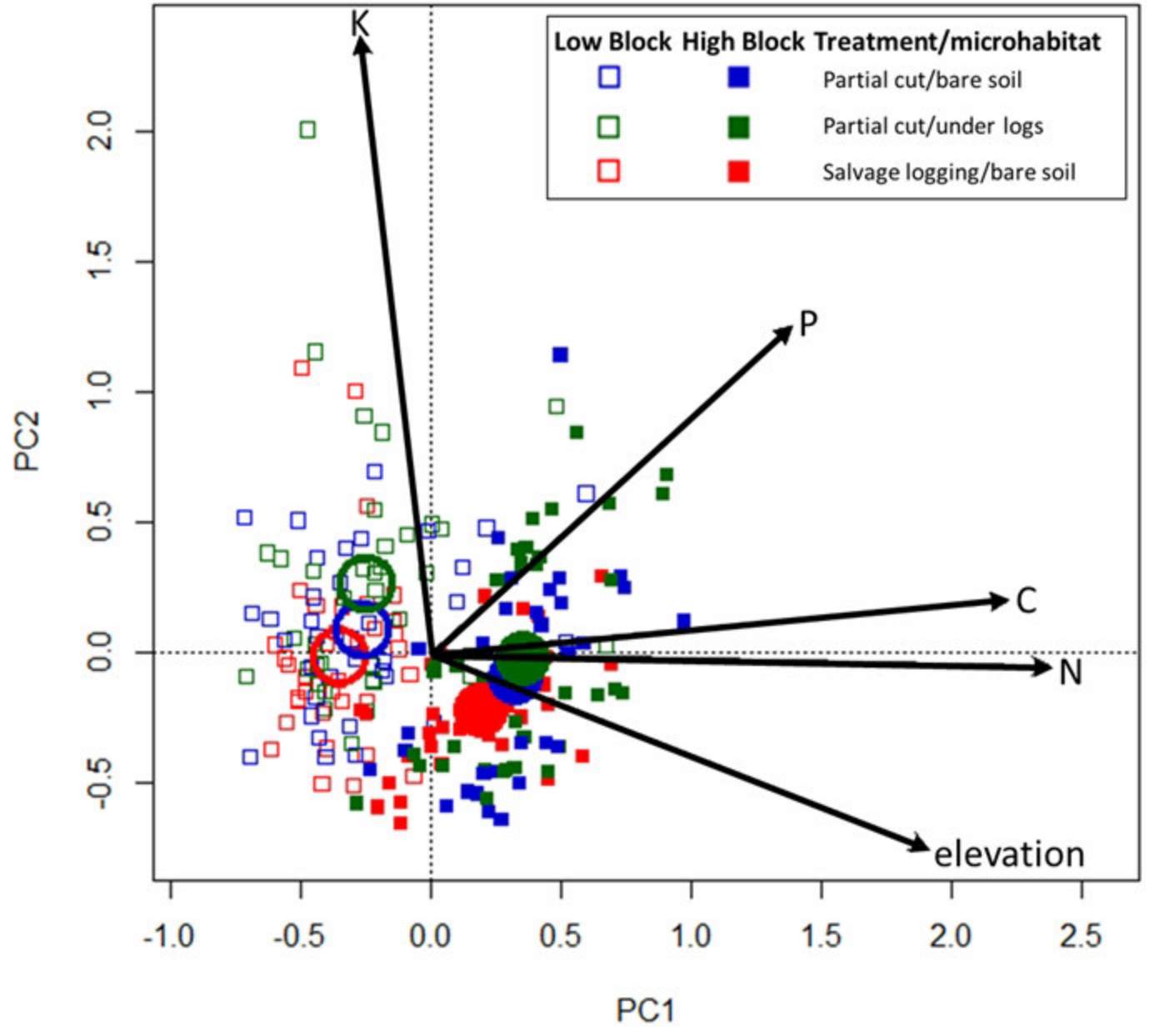
soil in red). Centroids (open dots for Low Block and filled dots for High Block) were drawn for each microhabitat within each dead-wood treatment and within each block, and follow the same colors as sampling points.


Sierra Nevada
0
10
20 km
High Block
(2053 m a.s.l.)
Low Block
(1477 m a.s.l.)
0
75
150 m
Dead-wood treatment
Partial cut
Salvage logging
Microhabitat
Bare soil
Under logs


Low Block
High Block
a)
b)
c)
d)
C (%)
N (%)
K (cmol$_+$kg^{-1})
P (ppm)
PC
SL


Low Block
High Block
a)
C (%)
3
2
1
b)
N (%)
0.20
0.15
0.10
0.05
c)
K (cmol$_+$kg^{-1})
0.5
0.4
0.3
0.2
0.1
0.0
d)
P (ppm)
6
4
2
0
PC/bare soil
SL/bare soil


Low Block
High Block
a)
b)
c)
d)
C (%)
N (%)
K (cmol$_+$kg^{-1})
P (ppm)
PC/bare soil
PC/under logs


Low Block
High Block
Treatment/microhabitat
Partial cut/bare soil
Partial cut/under logs
Salvage logging/bare soil
K
P
C
N
elevation
PC2
PC1
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5