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Impact of Native *Quercus robur* and Non-Native *Quercus rubra* on Soil Properties during Post-Fire Ecosystem Regeneration

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Abstract: Following disturbances, ecosystems are more susceptible to invasion by non-native species. Furthermore, it is important to determine the impact of alien tree species on soil regeneration processes during secondary succession. In this study, we analyzed the effect of native and late successional common oak (*Quercus robur*) and non-native red oak (*Q. rubra*) on soil physicochemical (pH, carbon, and nutrient content) and microbial properties (microbial biomass [Cmic] and respiration [RESP]) nearly 30 years after severe fire disturbance. Post-fire soils under *Q. rubra* had organic horizons with a greater mass, lower pH values, and depleted nutrient (N, Ca, K, Mg, and P) contents than soils under *Q. robur*. The impact of *Q. robur* as a late successional species on soil properties 30 years after a disturbance was similar to that of pioneer species (Scots pine, European larch, common birch, and black alder), as is indicated in previous studies. Most of the studied physicochemical (bulk density, soil organic carbon, N, Ca, K, and P content) and microbial (RESP and Cmic) soil parameters under *Q. robur* were within the ranges found for post-fire soils under pioneer tree species. Only the pH and Mg and Na contents in organic horizons were higher under *Q. robur* than under pioneer species. Our results indicate that *Q. robur* could be a valuable addition to reforestation sites after fire disturbance, especially in more fertile microhabitats. Due to the depletion of soil nutrients, care should be taken when introducing *Q. rubra* during the reforestation of post-fire sites, especially in larger groups.

Keywords: reforestation; ecosystem disturbance; alien species; nutrients; soil organic matter

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1. Introduction

Climate change is causing increasingly frequent extreme weather phenomena, such as hurricanes and droughts. Related fires cause large-scale transformations of forest ecosystems and landscapes [1,2]. Large-scale fires may cause unfavorable changes in forest ecosystems, including changes to many physical, chemical, mineralogical, and biological soil properties [3,4]. On the other hand, some studies have indicated that the rate of recovery of plant communities and ecosystems after a fire can be very fast, e.g., [5]. In some cases, however, fires may cause long-term changes in soil organic matter (SOM) storage [6,7], decreasing microbial biomass and activity [8,9], deterioration of soil structure and porosity [3], and considerable reduction in nutrient content and availability [3,4]. Fires may cause the regression of forest ecosystems to secondary succession stages [10–12], especially in the case of high-intensity forest fires, in which a significant part of the biomass has been burned [13,14]. Although recovery of vegetation after a fire is often very fast [5], in some cases succession may not regenerate tree cover within an acceptable timeframe for forestry after a disturbance [15]. This is because plant communities and tree regeneration as a result of succession are often heterogeneous and differ significantly from each other even within a small area [16]. Often, dense herbaceous vegetation that appears in the first stages of succession limits the regeneration of crown-forming trees [17]. Therefore, natural regeneration after a fire could be accelerated by reforestation with different tree species [18].

Pioneering species, such as Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Mill.), and common birch (*Betula pendula* Roth), are often used in the reforestation of post-fire sites in the temperate climate of Central Europe [19,20]. Late successional species, such as oaks (*Quercus* ssp.), have also been tested to a limited extent [19]. However, it remains unclear whether it is best to introduce only pioneer species immediately after a disturbance and then, after several decades, introduce late successional species [21], or to introduce late successional species immediately after a disturbance [21]. In Central Europe, a non-native species, red oak (*Q. rubra* L.), has been also introduced following fires [19] alongside native species, such as common (*Q. robur* L.) and sessile (*Q. petraea* (Matt.) Liebl.) oak. This was because *Q. rubra* has lower nutrient and water demands (i.e., better resistance to drought) than *Q. petraea* and *Q. robur* and, therefore, can be more vigorous and productive on less fertile sites [22].

Red oak is one of the most common alien species in European forests [23,24]. It was introduced to Europe in 1691 and currently covers about 350,000 ha across the whole continent, except the coldest part of Scandinavia and many Mediterranean areas [22]. Red oak is valued as a fast-growing species that provides valuable timber and, economically, is one of the most important non-native tree species in several European countries [22,25]. However, its invasive nature [26] and negative impacts on understory plant community biodiversity [27,28], physicochemical soil properties [26], and microbial biomass and activity [27] have been identified as problems when its compared to native tree species.

Following disturbances, ecosystems are more susceptible to invasion by non-native species [29,30]. Therefore, ecosystem invasibility is associated with disturbances [31,32]. For example, in some Mediterranean ecosystems, invasibility potential has risen alongside the increase in large, infrequent wildfires over the past few decades due to the proximity of urban and peri-urban areas to severely disturbed ecosystems [32]. Taking into account the consequences of ongoing climate change, including the projected dieback of forest stands and changes in tree species ranges [33], the role of alien species in soil recovery after disturbance requires careful consideration [34,35]. For example, the positive role of *Larix kaempferi* as an alien species in Japan for the recovery of forest ecosystems after wind disturbance was indicated [35]. On the other hand, it was pointed out that the negative impact of alien species on soil and related ecosystem processes may significantly facilitate environmental degradation [36].

To date, there have been no comparative studies on the impact of native and red oaks on the chemical and microbial properties of post-fire soils. The impact of tree species on soil properties varies depending on climate, parent rock, and type of disturbance [37,38]. Introducing oaks to nutrient-poor soils after fire disturbance may have different results than their introduction to optimal growth conditions. Usually, species with high fertility soils produce litters with a high nutrient content and decomposition rate. Furthermore, they are active in nutrient recycling compared to species characteristic of low fertility soils, which produce recalcitrant litters that retard nutrient recycling [39,40]. Some evidence suggests that tree species that produce litters with an intermediate nutrient content and decomposition rate may increase nutrient cycling in low nutrient soils and depress nutrient cycling in high nutrient soils [40]. This feedback between biotic factors and components of the physical environment requires management efforts in ecosystem restoration and the correct selection of tree species for reforestation [41,42].

This study aimed to compare the influence of native and late successional common oak (*Q. robur* L.) and non-native red oak (*Q. rubra* L.) on soil's physicochemical properties, microbial biomass, and respiration nearly 30 years after severe fire disturbance. We hypothesized that: (i) the impact of oaks as late successional species on post-fire soil properties will not differ from that of pioneer species (Scots pine [*P. sylvestris*], European larch [*L. decidua*], common birch [*B. pendula*], and black alder [*Alnus glutinosa* (L.) Gaertn.]) in previous studies (e.g., [20,38,43]; (ii) soils under common oaks will have better physicochemical parameters (e.g., higher pH and carbon and nutrient contents) than soils under red oaks.

2. Materials and Methods

2.1. Study Site

The study was conducted in southern Poland at a reforested post-fire site in Rudziniec Forest District (50° 17′ 37.3″ N; 18° 25′ 00.8″ E). The Rudziniec post-fire site had an average annual temperature of 9.7 °C, mean annual precipitation of 586 mm, an average number of days with rain of 168, and with snow of 45 (data for 1992–2022 was collected from meteorological station; source: www.tutiempo.net (accessed on 2 February 2023). A fire occurred in this area in August 1992 and was one of the largest post-World War II fires in Central Europe. The fire lasted 18 days and affected 9062 ha, including 8461 ha of forestland. The fire was of high severity, meaning that it caused more than 75% tree mortality and extensive mineral soil exposure. Before the fire, most of the burnt area had moderately moist and humid mixed pine-oak forests, with more than 5000 ha of mature stands. In the Rudziniec Forest District, 2154.3 ha of forest land was burned. Within three years of the fire, the remaining trees were cut, their stems and unburned parts removed, the wood/logs extracted, and the post-fire site was reforested [44,45].

2.2. Soil Sampling and Analysis

The sampling sites were in pure managed stands of common and red oak growing on sandy and loamy post-fire soils. The stand age ranged from 27 to 28 years. Based on the World Reference Base (WRB), the sandy soils were classified as Brunic Arenosols and Podzols, and the loamy soils were classified as Luvisols [46]. Both sands and loams on the research plots were fluvioglacial deposits from the Middle Polish Glaciation in the Pleistocene (source: Polish Geological Institute, http://geologia.pgi.gov.pl (accessed on 2 February 2023).

In total, 16 sampling plots (10 × 10 m) representing four replicates for each oak species and parent material (geological substrate) variant were established. The plots were localized with randomization and spaced at least 50 m apart from each other in order to avoid pseudoreplication. Samples from the uppermost mineral layer (A horizon; 0–5 cm depth) were collected from each sampling plot in September 2020. Each composite soil sample (1.0 kg mass of sample) comprised five subsamples taken from the middle and the corners of the sampling plot (i.e., the envelope sampling method). Independently, five samples per each plot with intact (natural) structures were collected in 100 cm^3 cylinders from 0 to 5 cm depth to determine their bulk density (BD). Samples from the organic horizons (Oi + Oe, litter layer) were collected from five 20 × 20 cm squares (0.04 m^2) in each study plot. Each sample of O_i + Oe horizons was weighed using an electronic balance with an accuracy of 1 g.

In the laboratory, the soil samples were sieved (2 mm mesh for mineral soil and 10 mm for O horizon) and split into two parts. One part was air-dried and used for physical, physicochemical, and chemical analyses, and the other part was stored field-moist at 4 °C and used for microbial analyses. The results of all analyses were expressed on a dry weight basis. The mineral soil subsamples were measured to determine their texture using a Laser Particle Sizer Analysette 22 MicroTec plus (Fritsch GmbH). The soil organic carbon (SOC) and total nitrogen (Nt) and sulfur (S) contents were determined using a LECO TruMac CNS analyzer (LECO Corporation, Michigan, St. Joseph, MI, USA). The soil pH was measured potentiometrically in H_2O (pH_{H2O}) at a 1:2.5 w/v ratio after 24 h equilibration. The total calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), and phosphorus (P) contents were determined following digestion in HNO_3 (nitric acid; d = 1.40) and 60% $HClO_4$ (perchloric acid) at a 4:1 ratio using inductively coupled plasma optical emission spectrometry (ICP-OES) with a Thermo Scientific iCAP 6000 series spectrometer (Waltham, MA, USA).

The subsamples from Oi + Oe (litter) horizons were oven-dried at 60 °C to remove moisture. The measured moisture loss was used to calculate the dry mass. Following moisture analysis, the subsamples were mixed to create a composite sample representing each plot. Then, the composite Oi + Oe samples were ground. Their pH_{H2O} was determined at a 1:5 w/v ratio after 24 h equilibration, while their C, N, and S contents were determined using a LECO TruMac CNS analyzer. Their total Ca, Mg, K, Na, and P contents were determined by atomic absorption spectrometry using ICP-OES (iCAP 6000 series spectrometer) following digestion in a mixture of HNO_3 (d = 1.40) and 60% $HClO_4$ (3:1 ratio).

To measure microbial biomass (Cmic) and respiration (RESP), samples (50 g d.w.) unamended for RESP measurements and amended with 8 mg glucose monohydrate for Cmic measurements were incubated at 22 °C in gas-tight jars. The incubation time was 24 h for the determination of RESP and 4 h for Cmic. The jars contained small beakers with 5 mL 0.2 M NaOH to trap the evolved CO_2. After the jars were opened, 2 mL 0.9 M $BaCl_2$ was added to the NaOH; the excess hydroxide was titrated with 0.1 M HCl in the presence of phenolphthalein as an indicator. Cmic was calculated from the substrate-induced respiration rate according to the equation: Cmic [mg g^{-1}] = 40.04 y + 0.37, where "y" is ml $CO_2 \times h^{-1} \times g^{-1}$.

The samples collected in cylinders with intact structure were passed through a sieve (2 mm mesh size), dried at 105 °C for 5 h, and then weighed. The weight was divided by volume of cylinders (100 cm^3) to obtain the bulk density (BD) of the fine fraction (<2 mm).

2.3. Data Evaluation

Data were analyzed with Statistica version 13.3 software (StaSoft Inc., Tulsa, OK, USA). A non-parametric Kolmogorov–Smirnov test was applied to check for significant differences in soil properties between the studied oak species and parent material type. Correlation analysis between the analyzed soil properties was performed using Spearman's correlation coefficient (r) at the significance level $p < 0.05$.

3. Results

3.1. Basic Soil Parameters

The sandy soils belonged to the sand, while loamy soils to silty loam textural classes. The sand, silt, and clay contents were 89:10:1 in the sandy and 47:48:6 in the loamy soils. The uppermost Oi + Oe and mineral (0–5 cm) soil horizons was acidic. The pH_{H2O} values in 0–5 cm horizons depended on oak species and was higher under *Q. robur* (pH_{H2O} = 4.1) than under *Q. rubra* (pH_{H2O} = 3.9). The BD values for the investigated species were similar. The mass of Oi + Oe horizons was higher under *Q. rubra* (7.9 kg m^{-2}) than under *Q. robur* (4.3 kg m^{-2}; Table 1).

Table 1. Texture, BD, pH_{H2O} and mass of Qi + Oe horizons for post-fire soils under common and red oak stands on reforested post-fire site.

Effect		**Soil Parameters/Horizons [cm]**						
		Sand (2.00–0.05 mm)	**Silt (0.05–0.002 mm)**	**Clay (<0.002 mm)**	**BD**	**pH_{H2O}**		**Mass (d. w.)**
		0–5 cm				**Oi + Oe**	**0–5 cm**	**Oi + Oe**
		[%]			**[g cm^{-3}]**			**[kg m^{-2}]**
Species	*Q. robur*	$65 \pm 9^{a,1}$	32 ± 8^{b}	3 ± 1^{a}	1.15 ± 0.04^{a}	5.0 ± 0.1^{a}	4.1 ± 0.0^{b}	4.3 ± 0.3^{a}
	Q. rubra	71 ± 8^{a}	26 ± 7^{a}	3 ± 1^{a}	1.24 ± 0.09^{a}	4.6 ± 0.2^{a}	3.9 ± 0.1^{a}	7.9 ± 1.3^{b}
Parent material	Sand	89 ± 1^{b}	10 ± 1^{a}	1 ± 0^{a}	1.12 ± 0.09^{a}	4.6 ± 0.1^{a}	4.0 ± 0.1^{a}	6.1 ± 1.2^{a}
	Loam	47 ± 3^{a}	48 ± 3^{b}	6 ± 0^{b}	1.27 ± 0.03^{a}	4.9 ± 0.2^{a}	4.0 ± 0.1^{a}	6.1 ± 1.1^{a}

[1] mean ± SE; within columns, means followed by different lowercase ([a], [b]) are significantly different (at $p < 0.05$).

3.2. Carbon and Macronutrient Content

The differences between SOC (Figure 1) and Nt (Figure 2) content in litter and 0–5 cm horizons in studied sandy and loamy soils were not significant. The SOC contents in litter and mineral soil (0–5 cm) horizon were similar under the investigated species (Figure 1). The Nt content in both litter and 0–5 cm horizons were higher under *Q. robur* (12.94 and 1.49 g kg^{-1}, respectively, for Oi + Oe and 0–5 cm horizons) than under *Q. rubra* (10.35 and 0.96 g kg^{-1}, respectively, for Oi + Oe and 0–5 cm horizons; Figure 2).

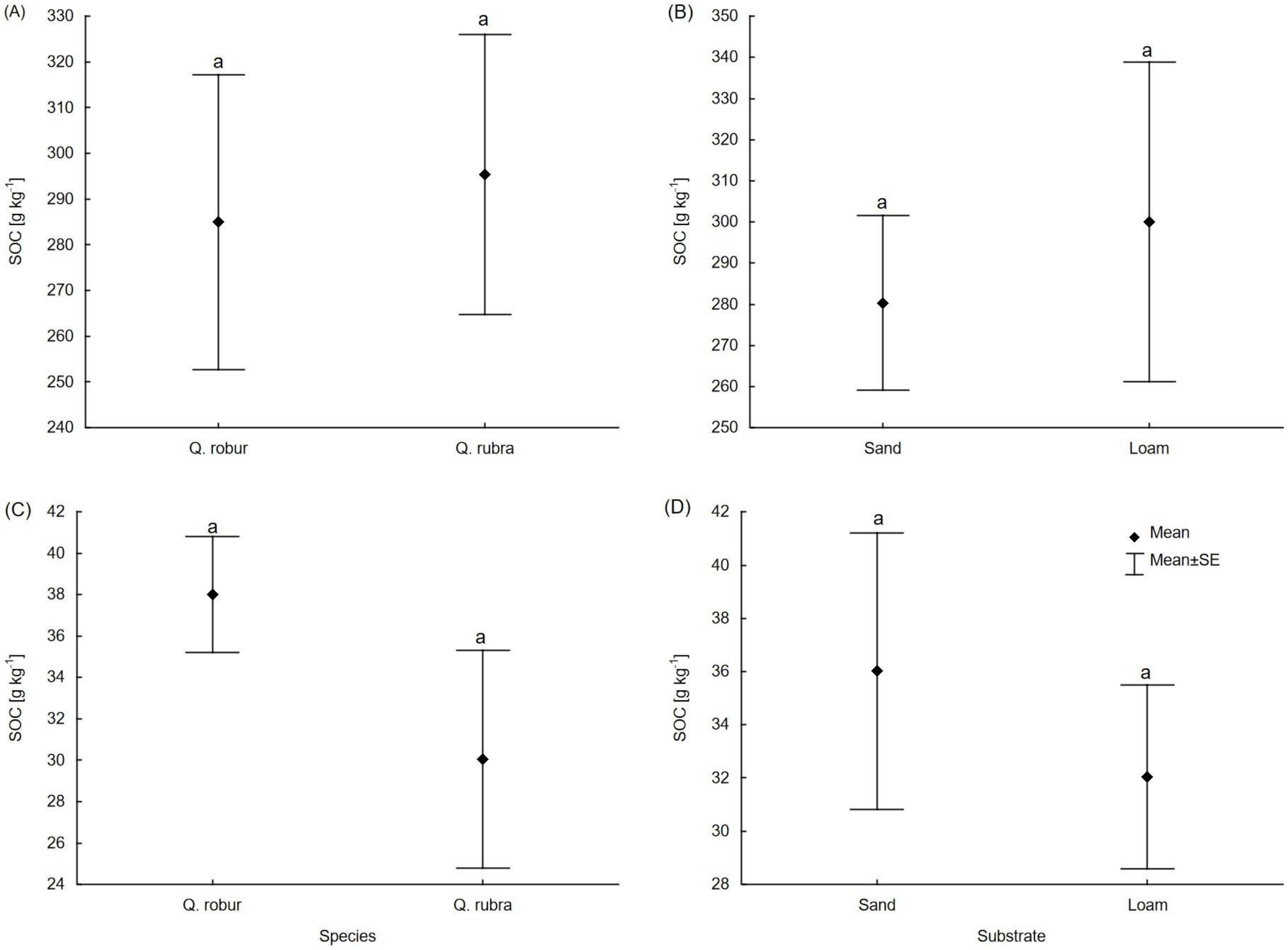

Figure 1. SOC content in litter Oi + Oe (**A**,**B**) and 0–5 cm mineral (**C**,**D**) horizons under common and red oak stands on studied post-fire site; means followed by the same lowercase (a) are not significantly different at $p < 0.05$.

The litter and mineral horizons of investigated post-fire soils under *Q. robur* contained more nutrients than post-fire soils under *Q. rubra.* The litter horizons under *Q. robur* had higher Mg and P contents than those under *Q. rubra*. The uppermost mineral soil under *Q. robur* had higher Ca, K, and Mg contents (Table 2).

The loamy soils had higher K and Na contents in litter horizons and Ca, K, Mg, and Na contents in 0–5 cm horizons (Table 2).

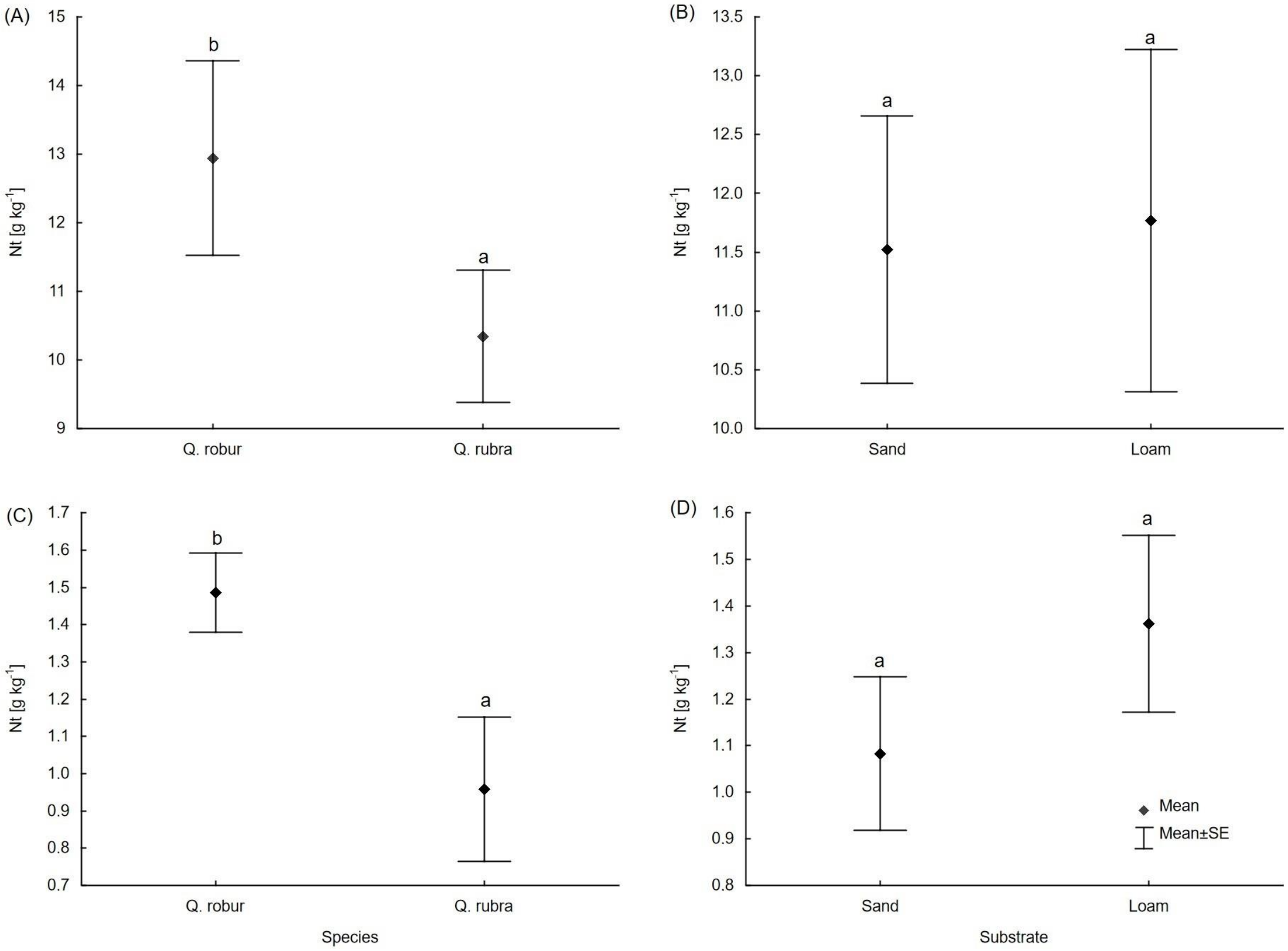

Figure 2. Nt content in litter Oi + Oe (**A**,**B**) and 0–5 cm mineral (**C**,**D**) horizons under two oak species on reforested post-fire site; means followed by different lowercase (a, b) are significantly different at $p < 0.05$.

3.3. Microbial Biomass and Respiration

Oak species and soil substrate had no significant effect on microbial biomass (Cmic) and respiration (RESP; Table 3).

3.4. Relationship between Soil Parameters

In 0–5 cm soil horizons, RESP was positively correlated with SOC (r = 0.68), S (r = 0.60), and P (r = 0.62) content and negatively correlated with BD (r = −0.68). Cmic was positively correlated with P content (r = 0.57) and negatively correlated with BD (r = −0.64). The SOC content was positively correlated with Nt (r = 0.84), S (r = 0.78) and P (r = 0.53) contents (Table 4).

Table 2. Nutrient (S, Ca, K, Mg, Na, and P) content in reforested post-fire soils under common and red oak stands.

Effect		**Nutrient/Horizons [cm]**											
		S		**Ca**		**K**		**Mg**		**Na**		**P**	
		Oi + Oe	**0–5 cm**	**Oi + Oe**	**0–5 cm**	**Oi + Oe**	**0–5 cm**	**Oi + Oe**	**0–5 cm**	**Oi + Oe**	**0–5 cm**	**Oi + Oe**	**0–5 cm**
		[%]								**[g kg^{-1}]**			
Species	*Q. robur*	1.20 ± 0.12 ^{a,1}	0.24 ± 0.02 ^{a}	4.62 ± 0.49	0.29 ± 0.05 ^{b}	1.32 ± 0.17 ^{a}	1.11 ± 0.26 ^{b}	1.12 ± 0.06 ^{b}	0.48 ± 0.12 ^{b}	0.06 ± 0.00 ^{a}	0.09 ± 0.01 ^{a}	0.73 ± 0.05 ^{b}	0.18 ± 0.02 ^{a}
	Q. rubra	1.10 ± 0.05 ^{a}	0.17 ± 0.03 ^{a}	3.50 ± 0.83	0.20 ± 0.04 ^{a}	1.17 ± 0.14 ^{a}	0.87 ± 0.23 ^{a}	0.78 ± 0.13 ^{a}	0.35 ± 0.10 ^{a}	0.07 ± 0.01 ^{a}	0.08 ± 0.01 ^{a}	0.57 ± 0.05 ^{a}	0.12 ± 0.02 ^{a}
Parent material	Sand	1.13 ± 0.07 ^{a}	0.18 ± 0.03 ^{a}	4.17 ± 0.72 ^{a}	0.13 ± 0.03 ^{a}	0.88 ± 0.07 ^{a}	0.37 ± 0.03 ^{a}	0.89 ± 0.14 ^{a}	0.14 ± 0.02 ^{a}	0.05 ± 0.00 ^{a}	0.05 ± 0.00 ^{a}	0.61 ± 0.06 ^{a}	0.14 ± 0.03 ^{a}
	Loam	1.17 ± 0.12 ^{a}	0.22 ± 0.02 ^{a}	3.95 ± 0.70 ^{a}	0.36 ± 0.03 ^{b}	1.61 ± 0.09 ^{b}	1.61 ± 0.11 ^{b}	1.02 ± 0.09 ^{a}	0.69 ± 0.06 ^{b}	0.08 ± 0.01 ^{b}	0.12 ± 0.00 ^{b}	0.69 ± 0.05 ^{a}	0.16 ± 0.02 ^{a}

^{1}. mean ± SE; within columns, means followed by different lowercase (^{a}, ^{b}) are significantly different (at $p < 0.05$).

Table 3. Microbial properties (Cmic and RESP) in post-fire soils under the influence of two oak species.

Effect		Characteristics/Horizons [cm]			
		RESP		Cmic	
		Oi + Oe	0–5 cm	Oi + Oe	0–5 cm
		[μM CO_2 g^{-1} 24 h^{-1}]		[μg g^{-1}]	
Species	*Q. robur*	40.96 ± 2.40 $^{a, 1}$	1.00 ± 0.08 ^{a}	2202.15 ± 180.01 ^{a}	169.89 ± 14.97 ^{a}
	Q. rubra	39.11 ± 11.21 ^{a}	0.94 ± 0.19 ^{a}	2187.37 ± 460.45 ^{a}	164.39 ± 29.77 ^{a}
Parent material	Sand	37.07 ± 6.07 ^{a}	1.07 ± 0.19 ^{a}	2143.74 ± 264.27 ^{a}	187.47 ± 29.29 ^{a}
	Loam	43.01 ± 9.60 ^{a}	0.87 ± 0.06 ^{a}	2245.78 ± 416.96 ^{a}	146.81 ± 11.67 ^{a}

[1]. mean ± SE; within columns, means followed by the same lowercase (^{a}) are not significantly different (at $p < 0.05$).

Table 4. Spearman's correlation coefficient (r) between RESP, Cmic, SOC and studied physicochemical soil properties in 0–5 cm mineral horizons in the studied post-fire sites.

	RESP	Cmic	SOC
Sand	0.09	0.19	−0.01
Silt	−0.05	−0.15	0.03
Clay	−0.33	−0.36	−0.29
pH	0.46	0.37	0.06
SOC	**0.68 ***	0.47	1.00
Nt	0.49	0.23	**0.84 ***
S	**0.60 ***	0.38	**0.78 ***
Ca	0.12	0.03	0.04
K	−0.01	−0.08	0.04
Mg	0.01	−0.07	0.01
Na	−0.15	−0.25	−0.09
P	**0.62 ***	**0.57 ***	**0.53 ***
BD	**−0.68 ***	**−0.64 ***	−0.48

* bold values indicate significant correlation coefficients at $p < 0.05$.

4. Discussion

Our results (Table 1) confirmed that organic horizons (Oi + Oe) under *Q. rubra* have a higher mass than those under native oak species [26,47]. The mass of Oi + Oe horizons under *Q. rubra* (Table 1) was also much higher than had been reported in previous studies in post-fire sites for soils under pioneer species: *L. decidua* (3.8 kg m^{-2}), *P. sylvestris* (2.6 kg m^{-2}), and *B. pendula* (2.6 kg m^{-2}) [20]. The introduction of *Q. rubra* into natural mixed oak-hornbeam forests may significantly alter organic horizons and cause a shift from Mull to Moder humus form [47] due to the recalcitrant nature of its litter [48,49].

The lower SOC content in soils under *Q. rubra* than in soils under native oaks has been reported in the literature [26] but remains unconfirmed in our study (Figure 1). However, our results suggest that, compared to *Q. robur*, *Q. rubra* depleted nutrients in the uppermost litter and mineral horizons of post-fire soils (Figure 1; Table 2). *Q. rubra* has also been found to deplete nutrients in less-fertile soils in reclaimed lignite open-cast mines in Germany [50] and in sandy soils in the Northeastern United States [51]. In a managed forest on undisturbed sites in Poland, soils beneath *Q. rubra* had lower organic C, total Mg, N, P, exchangeable Ca, Mg, N-NH_4, and N-NO_3 contents than soils under communities of native plants [26]. The lower content of nutrients in soils may be related to the higher growth parameters and nutrient storage of *Q. rubra* biomass compared to *Q. robur* biomass [50]. According to the Forest Data Bank (www.bdl.lasy.gov.pl; accessed on 5 February 2023), *Q. robur* stands on sandy post-fire soils have a diameter at breast height (DBH) of 5–6 cm and a height of 5–8 m, while *Q. rubra* stands have a DBH of 12–13 cm and a height of 11–12 m. The stands of both oak species achieved higher growth parameters on loamy post-fire soils than on sandy soils. The *Q. robur* stands on loamy soils had a DBH of 10– 11 cm and a height of 10–12 m. *Q. rubra* stands on loamy soils had a DBH of 10–14 cm and a height of 13–16 m. Another reason for the lower nutrient content in soils under red oak may be the barely biodegradable organic matter of this species and the greater nutrient storage in organic horizons of considerable thickness [50].

Despite the lower content of nutrients, the negative effect of *Q. rubra* on the microbial biomass and activity in both organic and mineral horizons (Table 3) has not been confirmed [27,52]. Microbial biomass often correlates with SOC, and a lack of SOC limits the growth and activity of microorganisms in the soil [53,54]. However, correlation analysis showed that in post-fire soils under oak species, the limiting factor for biomass and microbial activity was P content (Table 4). It has already been suggested that P may limit the development of soil microflora in post-fire soils, especially under N-fixing species [43]. While it is abundant in soils in organic and inorganic forms, P is the least available mineral to plants due to its high fixation in most soil conditions and slow diffusion [54].

Compared to previous studies conducted in post-fire sites, no differences were found in the impact on soil properties of *Q. robur* as a late successional species compared to those of other species that locally act as pioneer plants, such as *Larix decidua, Pinus sylvestris, Betula pendula, and Alnus glutinosa* [20,38,43]. Most physicochemical (BD, SOC, Nt, Ca, K, and P content) and microbial (RESP and Cmic) soil parameters under *Q. robur* were within the ranges found for post-fire soils under pioneer tree species. Only the pH and Mg and Na contents in organic horizons were higher under *Q. robur* than under pioneer species [20,38,43]. In afforested post-mining sites after lignite exploitation in the northwest of the Czech Republic, the rate of soil organic matter accumulation increased in order natural regeneration (spontaneous succession) < spruce < pine, oak < larch < alder < lime [55].

Our results indicate that *Q. robur* can be a valuable admixture in the reforestation of post-fire sites. In the case of forest plantations in post-fire Mediterranean sites, it was indicated that pines (mainly *Pinus nigra* Arn. and *P. halepensis* Mill.) and oaks (especially *Q. ilex* L.) should be combined to take advantage of the complementary features of both species groups—the faster growth of pines and the high fire resilience of oaks [56]. On the other hand, recently in the Mediterranean area, attempts have been made not to use pines in the reforestation of post-mining sites. This is due to the poor recovery success of pines after fires. Pine forests are also sensitive to fire, especially those from reforestation [57]. The possibility of introducing *Q. robur* in the first generation of stands was also indicated in reclaimed post-mining sites [58]. However, according to ecological requirements, *Q. robur* should be introduced into microhabitats characterized by higher fertility [59,60].

5. Conclusions

Thirty years after the fire disturbance, the influence of *Q. rubra* on soil properties was reflected in organic horizons with a higher mass, lower pH, and depleted nutrients than soils under *Q. robur.* The impact of *Q. robur* as a late successional species on soil properties was similar to that of pioneer species (pine, larch, birch, and alder) in previous studies. Therefore, *Q. robur* can be a valuable admixture to reforestation sites after fire disturbance, especially in more fertile microhabitats. Due to the depletion of nutrients in the soil, care should be taken with the introduction of *Q. rubra* to reforestation of post-fire sites, especially in larger groups. However, the impact of *Q. rubra* on soil properties should not be the only criterion for assessing the suitability of this species for reforestation, particularly given predicted climate changes, changes in tree ranges, and the search for substitutes for native species.

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