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Effects of red oak (*Quercus rubra* L.) and Scots pine (*Pinus sylvestris* L.) on early soil development during afforestation of nutrient-poor post-mining sands

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Abstract: The article aims to raise the knowledge on how the Northern red oak affects the soil formation and nutrient cycling compared to Scots pine during the early-stage reclamation of nutrient-poor mineral soil that originated in the deep soil layers in a former sand quarry. Furthermore, the aim is to also answer the question if the admixture of red oak helps to regenerate the soil properties more effectively than pure stands. Three treatments were established: pure red oak, pure pine, and a mixed stand, where organic [composite samples of L+F (litter and fermented), F+H (fermented and humic)] and mineral (A, C) soil horizons were analysed. The oak significantly outperformed the pine in the soil amelioration, showing elevated pH, higher base saturation, and enriched concentrations of basic cations in the humus horizons. The lower litter accumulation under the oak reflected the enhanced decomposability of its litter. A pattern of reduced cation exchange capacity, but the elevated base saturation of the oak soils suggested the development of a nutrient-rich microenvironment with a diminished risk of aluminium toxicity. Phosphorus remained critically limiting. The mixed stand exhibited intermediate properties closer to the pine stand, with the synergistic effects currently limited. Our results support red oak as an effective reclamation species for infertile post-mining soils, though sustained amelioration requires a decades-long perspective and integrated forest management strategies.

Keywords: development of soil layers; mine site restoration; nutrient cycling; post-mining substrates; soil amelioration

The reclamation of degraded land, such as sites subjected to mineral extraction, represents one of the critical challenges of contemporary forestry (Burger, Zipper 2018; Sheoran et al. 2010). The re-naturalisation of abandoned sand and gravel quarries through afforestation aims at restoring landscape ecological functions and establishing stable forest ecosystems on soils exhibiting extremely adverse physical and chemical properties (Macdonald et al. 2015; Young et al. 2022). Afforestation of mine sites is associated with a high risk of failure. The situation becomes considerably

more complex when the technical reclamation process does not include an overlay of the reconstructed topography with the topsoil taken from the area of the quarry before mining. Such an approach is significantly more beneficial from a reclamation perspective, particularly when the material that has not been temporarily stored is directly transferred from another part of the mining site (Ghose 2001; Van Gorp, Erskine 2011). Sandy substrates, particularly those originating from depths of several metres below the original ground surface, are characterised by low base saturation, low cation ex-

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change capacity, and insufficient reserves of readily available nutrients (Desie et al. 2021). These substantially impoverished conditions necessitate the careful selection of suitable tree species capable of both tolerating extreme soil conditions and progressively ameliorating the soil, i.e. enhancing the soil fertility through the accumulation of organic matter and nutrient cycling via litter fall and biomass decomposition (Sheoran et al. 2010; Macdonald et al. 2015). Despite the extensive use of tree planting in reclamation, species-specific effects on the early soil development under extremely nutrient-poor sandy substrates remain insufficiently quantified.

The most common tree species of nutrient-poor sandy sites within the lower vegetation zones of Central Europe include the sessile oak [*Quercus petraea* (Mattuschka) Liebl.] and Scots pine (*Pinus sylvestris* L.). Both tree species are frequently utilised in the reclamation of sandy soils (Pietrzykowski 2019). However, sessile oak grows extremely slowly under such conditions and competes poorly with pine in terms of the growth rate. Its maintenance within a stand is associated with higher silvicultural costs, whilst its soil amelioration potential is severely constrained in the long term by limited nutrient cycling. The cycling is limited by the low quantity of litterfall associated with its slow growth. Consequently, it cannot initially substantially contribute to the improvement of the mineral soil chemistry.

The introduced northern red oak (*Quercus rubra* L.) is regarded as a tree species whose establishment in stands presents certain risks with respect to its natural regeneration capacity, sometimes evaluated as having invasive potential, and in terms of reduced ground vegetation diversity (Woziwoda et al. 2014; Vor et al. 2015; Nicolescu et al. 2020). However, owing to its inherent properties, it demonstrates significantly higher vigour and competitive ability on nutrient-poor soils in comparison with the sessile oak. For this reason, it is utilised in European silvicultural practice, especially on such sites with a broadleaved admixture (Nicolescu et al. 2020). As a broadleaved tree species, it could contribute more effectively to soil restoration – specifically to the improvement in the soil chemistry on nutrient-poor sandy sites – than the pine (compare Augusto et al. 2002; Kacálek et al. 2017). Pine litterfall contains, in contrast to broadleaves, a high proportion of recalcitrant

compounds, which results in a slow nutrient return to the soil and the prolonged maintenance of low pH and low base saturation (Berger et al. 2015). The positive effect of admixing northern red oak on the soil chemistry has been demonstrated, for example, within its natural range in approximately 50-year-old loblolly pine stands (*Pinus taeda* L.; Polyakova, Billor 2007).

The dynamics of soil properties in young forest stands are determined primarily by the quality of their upper humic horizons (Muraškiene et al. 2025) and by the rate of organic matter decomposition (Ge et al. 2013). During the initial phase of surface humus formation, the following factors are critical: (i) the quantity and composition of the litterfall, (ii) the quality of the litterfall in terms of the C:N ratio, lignin content and other recalcitrant compounds, (iii) the structure and activity of soil fauna and microbial communities, and (iv) pedoclimatic conditions (Ponge 2013; Frouz 2017; Irshad, Frouz 2024). In sandy soils, the process is further adversely affected by the low sorption capacity, which significantly limits the retention of the released nutrients (Shepherd, Bennett 1998).

The aim of the study was to evaluate the influence of the northern red oak compared to the pure Scots pine and their mixture on the pedogenesis of the upper soil horizons following approximately 20 years of sand quarry reclamation. The specific research questions were: (i) How do the proportions and composition of the upper soil horizons differ under the individual stand types? (ii) What are the differences in the distribution of available macronutrients (N, P, K, Ca, Mg) among the stands? (iii) Does the admixture of northern red oak into Scots pine stands at this stand age ensure a measurable ameliorative effect on the soil chemistry and nutrient reserves?

MATERIAL AND METHODS

The condition of newly forming upper soil horizons was evaluated in the area of a former sand quarry in the Orlice Tableland (Orlická tabule; 50°11'N, 15°58'E) on a property managed by Hradec Králové Municipal Forests, Ltd., in the Czech Republic. Following the cessation of sand mining prior to the year 2000, the quarry area was solely shaped by mechanical means to the required topographic configuration. No nutrient replenishment was carried out through an overlay of forest topsoil mate-

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rial taken prior to the commencement of the sand extraction. The newly formed horizon thus consisted of an extremely poor sandy substrate originally situated at a depth of approximately 5 m below the original ground surface. The new oligotroph substrate was fully absent of topsoil. The study site represents an extreme case of a sandy post-mining substrate, which allows isolating species-driven effects on the soil development. The soil is developing towards a regosol.

The site, at an elevation of approximately 250 m a.s.l., is classified according to the potential natural forest community as a nutrient-poor pine-oak forest (anthropogenic variant; according to the forest site classification system of the Czech Republic, see Viewegh et al. 2003). Tree stands were subsequently established in this substrate, with a dominance of planted bare-root pine and groups of red oak regenerated by sowing.

Sampling of the new forming soil was carried out in the autumn of 2020 in an approximately 20-year-old northern red oak stand (area 0.05 ha), in an 18-year-old Scots pine stand (area 0.5 ha), and at the boundary between these stands where the influence of both tree species was evident. The stand density was approximately 2 700 trees per ha, the basal area reached ca 20 m² per ha for oak and 40 m² per ha for pine. The mean diameter at breast height (*DBH*) and height of the northern red oak was 9.6 cm and 7 m, and Scots pine was 14.2 cm and 9 m, respectively. Soil samples were collected in three replicates spaced at least 10 m apart under three treatments: northern red oak (red oak – RO), Scots pine (pine – Pi), and the soil beneath the mixture of these tree species (RO+Pi). Sampling was performed using a 25 × 25 cm pedological frame. Because of their limited thickness, the L (litter) and F (fermented) horizons and the F and H (humic) horizons were analysed as composite organic horizons (L+F and F+H, respectively). To achieve a sample of an adequate amount for the chemical analyses, the L+F and F+H horizons from each sampling location were represented by composite samples derived from three frames randomly positioned within 1 m². The third position of the frame was used for sampling the mineral horizons as well. The A horizon was collected in its entirety to allow for the determination of the dry matter content, the upper C horizon was sampled to a depth of ca 15 cm for the chemical analyses only. The average thickness of the humus horizons reached 1.6 cm, 2.2 cm and

2.1 cm for the A horizon and 2.3 cm, 0.8 cm, and 0.7 cm for RO, Pi and RO+Pi, respectively.

The laboratory determinations included the dry matter content (L+F, F+H and A horizons). In the F+H, A and C horizons, the analyses comprised the oxidisable organic carbon (C_{ox} ; Springel-Klee method), loss-on-ignition (*LOI*; determined by the heating loss methodology), nitrogen according to the Kjeldahl method, pH in H₂O and KCl (soil to solution ratios of 5 g:50 ml for the F+H horizon and 10 g:50 ml for the A and C horizons), characteristics of the sorption complex according to Kappen 1929 [exchangeable base cations (*BCC*), cation exchange capacity (*CEC*), hydrolytic acidity (as $CEC - BCC$) and base saturation (*BS*)], and plant-available nutrient content determined by Mehlich III extraction (Mehlich 1984). The macronutrients in the L+F horizon were analysed according to plant material analytical methods (in a solution of H₂SO₄ + H₂O₂ + Se), comparable with the International Co-operative Programme (ICP) Forests methodologies (Rautio et al. 2020).

Based on the dry matter content and nutrient composition of the individual samples taken from the respective horizons, the nutrient pools in the L+F, F+H and A horizons were calculated (g·m⁻²).

The analysed soil properties for the individual horizons and stand treatments were compared statistically using an analysis of variance (ANOVA), whereas Welch's test (Welch 1951; one-way test function) followed by Tukey's test were used in cases of heterogeneity of variance. The nutrient contents of the soil layers were compared by principal component analyses (PCAs). The analyses were performed in R statistical software (Version 4.5.1; R Core Team 2025). Differences were considered statistically significant at a significance level $P = 0.1$; nevertheless, the differences at $P = 0.05$ are highlighted in the results tables.

RESULTS

The organic-layer mass differed most clearly between the pure red oak and the other two treatments. Less dry matter accumulated under the northern red oak in both the L+F and F+H horizons, whereas the mixed stand resembled Scots pine rather than red oak in the amount of surface organic matter (Table 1). In the A horizon, the red oak showed a higher mean dry matter content, but this difference was not statistically significant.

<https://doi.org/10.17221/29/2026-JFS>Table 1. Dry matter and nutrient pools in soil horizons ($\text{g}\cdot\text{m}^{-2}$) according to each treatment compared by ANOVA or Welch test and subsequent Tukey test

Horizon	Treatment	Dry matter	N	P	K	Ca	Mg	C_{ox}	LOI
L+F	<i>P</i>	0.034	0.063	0.092	0.322	0.221	0.088	–	–
	Pi	502 ^a	5.0 ^a	0.35 ^a	0.63	2.46	0.22 ^b	–	–
	RO	269 ^b	2.0 ^b	0.17 ^b	0.75	4.30	0.36 ^a	–	–
	RO+Pi	482 ^a	4.5 ^{ab}	0.32 ^{ab}	0.85	3.31	0.29 ^{ab}	–	–
F+H	<i>P</i>	0.003	0.003	0.033	0.055	0.020	0.045	0.004	0.007
	Pi	3 270 ^a	30.7 ^a	0.08 ^{ab}	0.96 ^{ab}	4.93 ^a	0.44 ^{ab}	608 ^{ab}	1 527 ^a
	RO	1 436 ^b	6.4 ^b	0.06 ^b	0.54 ^b	1.93 ^b	0.21 ^b	137 ^b	329 ^b
	RO+Pi	3 508 ^a	41.8 ^a	0.13 ^a	1.66 ^a	5.11 ^a	0.52 ^a	989 ^a	2 191 ^a
A	<i>P</i>	0.371	0.480	0.167	0.045	0.171	0.307	0.504	0.539
	Pi	8 062	21.0	0.10	0.60 ^b	3.53	0.37	284	852
	RO	22 854	30.1	0.51	1.61 ^a	5.82	0.87	440	1 265
	RO+Pi	6 351	19.8	0.09	0.64 ^b	1.88	0.29	364	1 040
Together	<i>P</i>	0.190	0.070	0.620	0.143	0.552	0.183	0.023	0.022
	Pi	11 834	56.8 ^{ab}	0.52	2.20	10.92	1.02	892 ^{ab}	2 379 ^{ab}
	RO	24 560	38.4 ^b	0.74	2.90	12.04	1.44	576 ^b	1 595 ^b
	RO+Pi	10 342	66.2 ^a	0.54	3.15	10.30	1.10	1 353 ^a	3 231 ^a

^{a-c}statistically different groups within a given parameter and horizon; bold – differences at a significance level of $P = 0.1$; underlined – differences at $P = 0.05$; L+F – composite of litter and fermented horizons; F+H – composite of fermented and humic horizons; A – topsoil mineral horizon; Pi – Scotch pine; RO – Northern red oak; RO+Pi – soil beneath the mixture of the two species; C_{ox} – oxidisable organic carbon; LOI – loss-on-ignition

The nutrient composition of the upper humus horizons also separated the red oak from the other treatments, while the mixed stand remained closer to the pine in the PCA ordination. In the L+F horizon, the red oak differed from the other treatments by lower N and higher K, Ca and Mg contents; in the F+H horizon, it differed mainly by lower N and at $P = 0.1$, and also higher P contents (Figure 1; Tables 2, 3). The admixture effect of red oak into the pine was detectable in the L+F horizon only, where the mixed stand showed higher K and Mg contents than the pure pine, while Ca was also higher, but not significantly (Figure 1; Table 2).

In the mineral soil, the treatment differences in the nutrient concentrations were limited and horizon-specific. In the A horizon, the Scots pine had higher Ca and lower P contents than the red oak, whereas in the C horizon, the only confirmed difference concerned a lower Ca content under the red oak. No statistically significant treatment differences in the C:N ratio were found in any horizon, although the mean C:N ratio was highest in the mixed stand in both the F+H and A horizons (Table 3).

Patterns in the nutrient pools differed from those observed for the nutrient concentrations. In the L+F horizon, despite the lower dry matter under the red oak, significant differences in the nutrient pools were detected only at $P = 0.1$, namely lower N and P pools and higher Mg pools under the red oak (Table 1). In the F+H horizon, the red oak had lower pools of all macronutrients, with the clearest differences relative to the mixed stand and less pronounced differences relative to the pine. In the A horizon, the mean nutrient pools were higher under the red oak due to the higher mean dry matter content, but a statistically significant difference was confirmed only for K (Table 1). The mixture effect was obvious in the chemistry of the whole analysed profile. Overall, the mixed stand was lowest in the mean dry matter, but in N ($P = 0.07$ only), C and LOI contents it was higher than the red oak (Table 1).

The soil acidity showed the clearest advantage of the red oak in the F+H horizon, whereas the differences became weaker with depth. In the F+H horizon, the red oak had a higher pH in both H_2O and KCl than the other treatments (Table 4). In the A horizon, the pH also differed among the treat-

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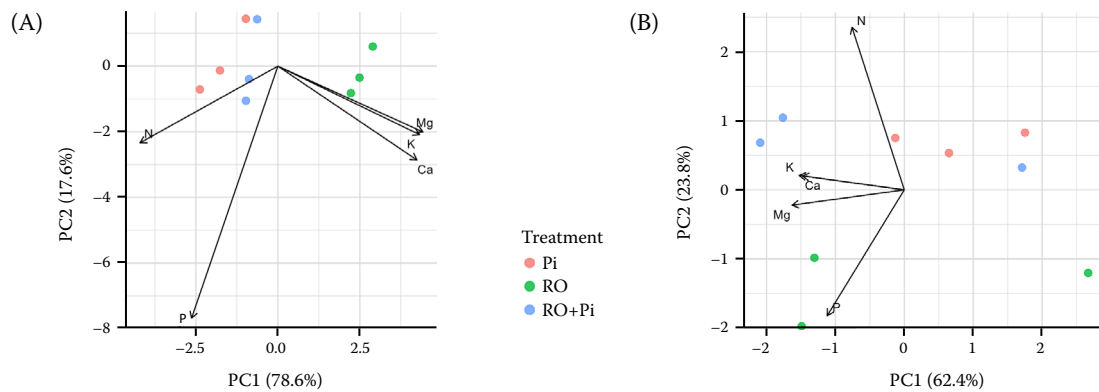


Figure 1. Principal component analysis (PCA) graph of nutrient content (A) in the L+F (composite of litter and fermented horizons) and (B) F+H (composite of fermented and humic horizons)

Pi – Scotch pine; RO – Northern red oak; RO+Pi – soil beneath the mixture of the two species

Table 2. Nutrient contents in the L+F horizon (plant material analytical methods; %) according to each treatment compared by ANOVA with subsequent Tukey test

Horizon	Treatment	N	P	K	Ca	Mg
	<i>P</i>	<u>0.022</u>	0.518	< 0.001	< 0.001	< 0.001
L+F	Pi	0.970 ^a	0.068	0.127 ^c	0.470 ^b	0.044 ^c
	RO	0.736 ^b	0.062	0.280 ^a	1.580 ^a	0.136 ^a
	RO+Pi	0.944 ^a	0.067	0.177 ^b	0.690 ^b	0.060 ^b

^{a-c}statistically different groups within a given parameter; bold – differences at a significance level of $P = 0.1$; underlined – differences at $P = 0.05$; L+F – composite of litter and fermented horizons; Pi – Scotch pine; RO – Northern red oak; RO+Pi – soil beneath the mixture of the two species

Table 3. Chemical properties of the F+H, A and C horizons according to each treatment: C:N ratio and nutrient content (Mehlich III extraction)

Horizon	Treatment	C:N	N (%)	P (mg·kg ⁻¹)	K (mg·kg ⁻¹)	Ca (mg·kg ⁻¹)	Mg (mg·kg ⁻¹)
F+H	<i>P</i>	0.258	<u>0.006</u>	0.104	0.253	0.950	0.805
	Pi	19.8	0.93 ^a	22.7 ^b	288.7	1494.7	132.0
	RO	20.4	0.46 ^b	44.7 ^a	382.7	1410.7	148.0
	RO+Pi	23.6	1.18 ^a	36.0 ^{ab}	466.7	1452.0	147.3
A	<i>P</i>	0.276	0.178	0.080	0.327	<u>0.006</u>	0.248
	Pi	14.5	0.25	12.3 ^b	74.7	434.3 ^a	45.7
	RO	14.5	0.16	20.3 ^a	82.7	263.3 ^b	40.3
	RO+Pi	18.2	0.38	13.3 ^{ab}	117.7	304.7 ^b	48.3
C	<i>P</i>	0.790	0.935	0.618	0.380	0.087	0.961
	Pi	17.2	0.07	23.3	36.0	192.7 ^a	30.3
	RO	15.8	0.07	20.7	32.0	150.3 ^b	30.0
	RO+Pi	17.4	0.06	20.0	32.0	168.7 ^{ab}	30.0

^{a-c}statistically different groups within a given parameter and horizon; bold – differences at a significance level of $P = 0.1$; underlined – differences at $P = 0.05$; L+F – composite of litter and fermented horizons; F+H – composite of fermented and humic horizons; A, C – mineral horizons; Pi – Scotch pine; RO – Northern red oak; RO+Pi – soil beneath the mixture of the two species

Table 4. Chemical properties of the F+H, A, and C horizons according to each treatment

Horizon	Treatment	pH _{H₂O}	pH _{KCl}	BCC (mval·100 g ⁻¹)	CEC – BCC (mval·100 g ⁻¹)	CEC (mval·100 g ⁻¹)	BS (%)	C _{ox} (%)	LOI (%)
F+H	<i>P</i>	0.003	0.001	0.863	0.008	0.060	0.004	0.009	0.020
	Pi	4.9 ^b	3.8 ^b	16.6	22.0 ^{ab}	38.5 ^{ab}	43.1 ^b	18.5 ^{ab}	46.2 ^{ab}
	RO	5.5 ^a	4.5 ^a	14.3	7.9 ^b	22.2 ^b	65.1 ^a	9.6 ^b	23.7 ^b
	RO+Pi	4.7 ^b	3.4 ^b	16.0	30.5 ^a	46.5 ^a	34.0 ^b	27.9 ^a	62.1 ^a
A	<i>P</i>	0.055	0.031	0.003	0.027	0.028	0.001	0.104	0.036
	Pi	5.1 ^{ab}	3.8 ^{ab}	4.8 ^a	7.0 ^{ab}	11.7 ^{ab}	40.7 ^a	3.6 ^{ab}	10.7 ^{ab}
	RO	5.4 ^a	3.9 ^a	1.5 ^b	4.3 ^b	5.8 ^b	26.6 ^b	2.2 ^b	6.1 ^b
	RO+Pi	4.8 ^b	3.3 ^b	3.0 ^b	11.4 ^a	14.5 ^a	21.1 ^b	7.0 ^a	19.0 ^a
C	<i>P</i>	0.134	0.186	0.198	0.458	0.738	0.134	0.996	0.543
	Pi	5.6	4.1	1.3	3.3	4.6	26.6 ^a	1.1	3.2
	RO	5.6	4.1	0.6	3.6	4.1	13.7 ^{ab}	1.1	3.6
	RO+Pi	5.4	4.0	0.5	3.9	4.3	10.6 ^b	1.1	3.7

^{a-c}statistically different groups within a given parameter and horizon; bold – differences at a significance level of $P = 0.1$; underlined – differences at $P = 0.05$; F+H – composite of fermented and humic horizons; A, C – mineral horizons; Pi – Scotch pine; RO – Northern red oak; RO+Pi – soil beneath the mixture of the two species; BCC – exchangeable base cations; CEC – BCC – hydrolytic acidity; CEC – cation exchange capacity; BS – base saturation; C_{ox} – oxidisable organic carbon; LOI – loss-on-ignition

ments, but the pattern was weaker; in the C horizon, no significant pH differences were confirmed (Table 4).

Most sorption-complex and organic-matter characteristics did not indicate a general increase under the red oak; instead, the red oak combined higher base saturation in the F+H horizon with lower values of several other parameters. Except for the base saturation in the F+H horizon, the red oak showed lower values of the sorption-complex characteristics in both the F+H and A horizons, together with lower C_{ox} and LOI contents in F+H. These differences were confirmed more often against the mixed stand than against the pure pine stand (Table 4).

DISCUSSION

The formation of the upper soil horizons in sandy substrates is a slow process, dependent on both the quantity of litterfall and the rate of its decomposition. After 20 years of the tree-mediated nutrient cycling, the thickness of the newly formed soil horizons remains low across all the treatments in our experiment. In the area, for example, the 60-year-old stands of pine and red oak growing on permanent forest land had an average thickness of the A horizon of 4.6 cm and 5.2 cm, respectively (un-

published data). As expected, the nutrient pools of experimental stands also remain significantly lower than the nutrients beneath the permanent forest. A mature pine stand, in 2.3 times higher dry matter of organic horizon, accumulated over 3 times more N and P, 2.6 times more Mg and 1.4 times more Ca, the nutrient pools in A were up to 2 times higher (in Ca; unpublished data) than pine in the presented plot in a former sand quarry.

The lower dry matter content that we confirmed in the L+F and F+H horizons beneath RO compared with Pi cannot be simply interpreted as a weaker ameliorative effect. It conversely reflects better litter decomposability under RO. This result can be interpreted in the context of differing litter properties: RO produces foliar litter with a lower lignin content and higher decomposability (cf. Wei et al. 2020). In contrast, pine litter contains high proportions of recalcitrant compounds, including lignin and terpenes, which microbial communities degrade more slowly (Park et al. 2018; Stuckenberg et al. 2025). The available studies suggest that young oak stands have a higher annual litterfall than young pine stands (Carnol, Bazgir 2013; Uri et al. 2022; Turski et al. 2024); however, there are insufficient direct measurements for red oak (e.g. Čiudienė et al. 2017). From a long-term per-

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spective, the lower litter accumulation beneath RO need not necessarily represent a disadvantage, as more efficient decomposition leads to a faster nutrient return to more readily available forms for plant uptake (Ponge 2013).

The observation that the mixed stand exhibited a dry matter content in the L+F and F+H horizons similar to Pi suggests that the presence of foliar litter from the northern red oak has not yet created a significant synergistic effect on the reduction of organic layer mass. However, the literature on the effects of species diversity on litter decomposition indicates that the addition of broadleaf litter can accelerate the decomposition of coniferous litter due to its superior quality and higher nitrogen content (Polyakova, Billor 2007). Nevertheless, this acceleration is conditioned by the environmental context in which the litter decomposition proceeds (Prescott et al. 2000; Zhang et al. 2008). In our case, however, this acceleration has not yet been sufficiently pronounced to result in a reduction in the total dry matter mass of organic horizons beneath the mixed stand.

The principal component analysis of macronutrient contents in the L+F and F+H horizons demonstrated that the nutrient profile of the mixed stand also more closely resembled Pi than RO. This suggests that the pine needles in the mixed stand continue to represent the dominant substrate controlling nutrient cycling as well. Beneath RO, the L+F horizon exhibited a statistically significantly lower N content and a higher K, Ca, and Mg content (Table 2), consistent with the higher base cation content of the oak foliage (Hallett, Hornbeck 1997). These differences are critically important in the context of post-mining land reclamation, where the increased pH and base saturation are recognised as essential outcomes of successful soil revitalisation (Sheoran et al. 2010; Ippolito et al. 2024). However, this ameliorative effect remains somewhat limited in the above-ground humus layers. The soil improvement potential of RO was only partially manifested in the F+H and A horizons, only in terms of the nutrient concentration rather than the nutrient pools (Table 1), and in the selected sorption complex parameters (Table 4). The lower pools of all the macronutrients in the F+H horizon beneath RO compared with the mixed treatment (and often also compared with Pi) suggests that the more intensive decomposition of broadleaf litter likely leads not only to more effi-

cient nutrient transport as you move down the soil profile, but also to nutrient losses through mineralisation and leaching.

The phosphorus beneath RO showed an interesting pattern: higher available P in both the F+H and A horizons (Table 3), yet lower total P pools (Table 1). This can be explained by the fact that while the broadleaf litter contains a higher P content, the more intensive decomposition leads to the faster P release and subsequent leaching (Zönnchen et al. 2014; mean P pools in the A horizon beneath RO were higher, albeit not statistically significant), or to immobilisation by the soil microflora. Phosphorus is a limiting nutrient in sandy soils, with its retention severely constrained by the deficiency of clay minerals and iron/aluminium oxides that would enable chemical P fixation (Borggaard et al. 1990), and by the low organic matter content (Ritchie, Weaver 1993). These results suggest that the sandy substrates after 20 years of afforestation still lack the capacity to effectively retain the released P.

The higher dry matter content of the A horizon beneath RO (albeit without any statistical significance) was accompanied by the higher mean macronutrient pools, although only the available K content was statistically significantly increased. This suggests that the RO litter gradually contributes to the enrichment of mineral horizons. However, this raises a puzzling observation: namely, the lower Ca content and pool in the A and C horizons beneath RO. This could be explained by the intensive Ca uptake by the trees and its preferential reallocation to the tree bodies and foliar biomass at the expense of fine root tissues (thereby depleting Ca from the fine root residues that decompose within the A and C horizons). Conversely, the lower available P in the F+H and A horizons beneath Pi may be attributable to its limited availability in the pine litter combined with the potential P fixation in these nutrient-poor, oxidic substrates.

The higher soil pH beneath RO compared with Pi represents an evident manifestation of the red oak's superior ameliorative potential. The pH differences progressively diminished with increasing depth in the soil. The elevated pH is a direct consequence of the higher base cation content in the broadleaf litter (confirmed for K, Ca, and Mg in the L+F horizon) and their release during litter decomposition, which contributes to the neutral-

isation of the soil acidity (Tóth et al. 2011). This increase probably also reflects a higher base saturation (*BS*) in the F+H horizon.

The character of the sorption complex revealed a particular paradox: beneath RO, lower cation exchange capacity (*CEC*) was recorded, yet concurrently higher base saturation (*BS*). This indicates that RO creates a soil environment with a lower organic matter content (and consequently fewer exchange sites), but with a proportionally higher abundance of base cations (Gruba, Mulder 2015). The higher *BS* shows a reduced risk of aluminium toxicity and improved nutrient availability for plant uptake (Bojórquez-Quintal et al. 2017; Olorunfemi et al. 2018).

The mixed treatment exhibited soil properties closer to Pi across multiple parameters, indicating the current dominance (i.e. within the initial twenty years of reclamation) of the pine litter effect. This is consistent with the anticipated biomass allocation of the two species, as Pi exhibits higher productivity on these nutrient-poor substrates. However, certain parameters (namely, higher pools of N, P, Ca, and Mg in the F+H horizon; higher *BS*) provide evidence of a measurable contribution of the presence of RO to the soil nutrient enrichment. These findings align with the literature on mixed-species stands, where synergistic effects (Liu et al. 2020) primarily manifest over longer temporal scales. Specifically, the positive impacts of species diversity on nutrient cycling and humus decomposition typically become statistically demonstrable only after 30–50 years of stand development (Cremer, Prietzel 2017; Rothe et al. 2002).

Soil microflora also play an important role: pine needles and oak foliage support the establishment of distinct microbial communities. Ectomycorrhizal fungi are more strongly associated with nutrient-poor soils and coniferous substrates, whereas arbuscular mycorrhizae are favoured in more nutrient-rich environments (Hedénc et al. 2023).

The carbon-to-nitrogen ratio (C:N) showed no statistically significant differences among the treatments across all the horizons. This finding is consistent with the observation that in early pedogenic stages, the C:N ratio is primarily determined by the quality of the incoming biomass, which only changes gradually over time (Zhou et al. 2019).

Pedogenesis on sandy substrates derived from former sand quarries exhibits distinctive characteristics that diverge markedly from those of estab-

lished forest soils. The first operative mechanism includes the gradual accumulation of organic matter, which progressively generates sorption sites and enhances the physical properties of the developing soil (Bartuska, Frouz 2015; Voltr et al. 2021). The second mechanism involves the release of base cations from the litter, which can incrementally lead to an increase in the base saturation and soil pH (Desie et al. 2020). Additionally, the progressive differentiation of soil microbial communities occurs, accompanied by increasing faunal biodiversity (Ponge 2003), processes which collectively enhance the nutrient cycling efficiency (Speckert et al. 2024).

The organic matter exhibits a dual functionality in these post-mining substrates. On one hand, it serves as a source of nutrient release and the primary generator of sorption sites. On the other hand, when accumulating excessively, it can impede efficient nutrient cycling (Bradley, Fyles 1996). This duality is particularly crucial for interpreting the lower oxidisable organic carbon (C_{ox}) and loss-on-ignition observed beneath RO. The lower C_{ox} content may favour nutrient bioavailability; however, this potential advantage is concurrently counterbalanced by the reduced sorption capacity of the substrate.

The study results demonstrate that after approximately twenty years of upper horizon development, RO exhibits measurable ameliorative effects compared with Pi – notably an elevated soil pH and a higher base cation content – although the overall soil improvement trajectory remains modest. This finding aligns with the established literature indicating that the restoration of soil fertility on nutrient-impoorished substrates represents a gradual process typically requiring several decades (Burger, Zipper 2018; Sheoran et al. 2010). Pedogenesis on sandy substrates proceeds characteristically slowly, with the fundamental limiting factor still being the inherently low sorption capacity of these soils, which severely constrains the effective retention of newly released nutrients (Weil, Brady 2017). In the specific context of nutrient-poor sandy conditions of a post-mining site, the absence of topsoil replacement prior to afforestation means that the soil formation proceeds exclusively from deeply buried alluvial material, lacking the initial nutrients typically accumulated in natural soil profiles. Within this challenging pedogenic setting, RO demonstrates a superior functional capacity relative to Pi

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in ameliorating the developing soil conditions. Its strategic role should be taken primarily as a long-term investment in progressive soil condition improvement rather than as a mechanism for rapid fertility restoration.

CONCLUSION

The tree species identity strongly influenced the early pedogenesis within two decades of afforestation on the nutrient-poor sandy post-mining substrate at the analysed site. The red oak exhibited a more pronounced ameliorative effect than the Scots pine, particularly in the humus horizons, as reflected by the higher pH, increased base saturation, and elevated concentrations of exchangeable base cations (K, Ca, Mg). These changes indicate a faster transition from acidic, oligotrophic conditions of the sandy substrate towards a more chemically favourable soil environment. The lower accumulation of organic matter under the red oak reflects enhanced litter decomposability and accelerated nutrient cycling, in contrast to the slower decomposition and persistent organic layer typical of pine stands. However, this more dynamic nutrient turnover is accompanied by lower nutrient pools in the forest floor and potential nutrient losses under low sorption capacity conditions. The combination of lower cation exchange capacity and higher base saturation under the red oak suggests improved nutrient availability despite limited retention capacity, indicating a reduced aluminium toxicity risk relative to pine soils.

In mixed stands, the total N and C_{ox} pools and also loss-on-ignition were increased. The other soil properties remained largely similar to the pine stands, demonstrating the current dominance of the conifer-driven processes. Only limited indications of the red oak influence were detected, suggesting that the synergistic effects of the admixture are still weak at this stage of stand development. Phosphorus remained a key limiting element across all the treatments, with increased mobilisation under the red oak, which carries the risk of leaching in substrates with limited sorption capacity.

Our results, although based only on one experimental site, support red oak as an effective component of reclamation strategies for nutrient-poor post-mining substrates, particularly where topsoil was not placed over the newly formed terrain. The use of this tree species in small pure regenera-

tion patches and in mixed stands can help to create a heterogeneous environment that reduces the risks associated with red oak cultivation and, as a result, can accelerate new-forming soil improvement and lead to increased biodiversity in the revitalised environment of former sand-mine areas.

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REFERENCES

- Augusto L., Ranger J., Binkley D., Rothe A. (2002): Impact of several common tree species of European temperate forests on soil fertility. *Annals of Forest Science*, 59: 233–253.
- Bartuska M., Frouz J. (2015): Carbon accumulation and changes in soil chemistry in reclaimed open-cast coal mining heaps near Sokolov using repeated measurement of chronosequence sites. *European Journal of Soil Science*, 66: 104–111.
- Berger T.W., Duboc O., Djukic I., Tatzber M., Gerzabek M.H., Zehetner F. (2015): Decomposition of beech (*Fagus sylvatica*) and pine (*Pinus nigra*) litter along an Alpine elevation gradient: Decay and nutrient release. *Geoderma*, 251–252: 92–104.
- Bojórquez-Quintal E., Escalante-Magaña C., Echevarría-Machado I., Martínez-Estévez M. (2017): Aluminum, a friend or foe of higher plants in acid soils. *Frontiers in Plant Science*, 8: 1767.
- Borggaard O.K., Jørgensen S.S., Moberg J.P., Raben-Lange B. (1990): Influence of organic matter on phosphate adsorption by aluminium and iron oxides in sandy soils. *Journal of Soil Science*, 41: 443–449.
- Bradley R.L., Fyles J.W. (1996): Interactions between tree seedling roots and humus forms in the control of soil C and N cycling. *Biology and Fertility of Soils*, 23: 70–79.
- Burger J.A., Zipper C.E. (2018): *How to Restore Forests on Surface-Mined Land*. Virginia, Virginia State University: 20.
- Carnol M., Bazgir M. (2013): Nutrient return to the forest floor through litter and throughfall under 7 forest species after conversion from Norway spruce. *Forest Ecology and Management*, 309: 66–75.
- Čiudienė D., Aleinikovienė J., Muraškienė M., Marozas V., Armolaitis K. (2017): Release and retention patterns of organic compounds and nutrients after the cold period in foliar litterfall of pure European larch, common beech and red oak plantations in Lithuania. *Eurasian Soil Science*, 50: 49–56.

<https://doi.org/10.17221/29/2026-JFS>

- Cremer M., Prietzel J. (2017): Soil acidity and exchangeable base cation stocks under pure and mixed stands of European beech, Douglas fir and Norway spruce. *Plant and Soil*, 415: 393–405.
- Desie E., Vancampenhout K., Nyssen B., Van Den Berg L., Weijters M., Van Duinen G.J., Den Ouden J., Van Meerbeek K., Muys B. (2020): Litter quality and the law of the most limiting: Opportunities for restoring nutrient cycles in acidified forest soils. *Science of the Total Environment*, 699: 134383.
- Desie E., Muys B., Jansen B., Vesterdal L., Vancampenhout K. (2021): Pedogenic threshold in acidity explains context-dependent tree species effects on soil carbon. *Frontiers in Forests and Global Change*, 4: 679813.
- Frouz J. (2017): Effects of soil development time and litter quality on soil carbon sequestration: Assessing soil carbon saturation with a field transplant experiment along a post-mining chronosequence. *Land Degradation & Development*, 28: 664–672.
- Ge X., Zeng L., Xiao W., Huang Z., Geng X., Tan B. (2013): Effect of litter substrate quality and soil nutrients on forest litter decomposition: A review. *Acta Ecologica Sinica*, 33: 102–108.
- Ghose M. (2001): Management of topsoil for geo-environmental reclamation of coal mining areas. *Environmental Geology*, 40: 1405–1410.
- Gruba P., Mulder J. (2015): Tree species affect cation exchange capacity (CEC) and cation binding properties of organic matter in acid forest soils. *Science of the Total Environment*, 511: 655–662.
- Hallett R.A., Hornbeck J.W. (1997): Foliar and soil nutrient relationships in red oak and white pine forests. *Canadian Journal of Forest Research*, 27: 1233–1244.
- Heděnc P., Zheng H., Pessanha Siqueira D., Lin Q., Peng Y., Kappel Schmidt I., Guldborg Frøslev T., Kjølner R., Rousk J., Vesterdal L. (2023): Tree species traits and mycorrhizal association shape soil microbial communities via litter quality and species mediated soil properties. *Forest Ecology and Management*, 527: 120608.
- Ippolito J.A., Li L., Banet T., Brummer J.E., Buchanan C., Betts A.R., Scheckel K., Basta N., Brown S.L. (2024): Soil health as a proxy for long-term reclamation success of metal-contaminated mine tailings using lime and biosolids. *Soil & Environmental Health*, 2: 100096.
- Irshad S., Frouz J. (2024): How the effect of earthworms on soil organic matter mineralization and stabilization is affected by litter quality and stage of soil development. *Biogeochemistry*, 167: 1425–1436.
- Kacálek D., Mauer O., Podrázský V., Slodičák M., Houšková K., Špulák O., Souček J., Novák J., Jurásek A., Leugner J., Dušek D. (2017): Meliorační a zpevňující funkce lesních dřevin. *Kostelec nad Černými lesy, Lesnická práce*: 300. (in Czech)
- Kappen H. (1929): *Die Bodenazidität*. Berlin, Springer: 363. (in German)
- Liu J., Liu X., Song Q., Compson Z.G., LeRoy C., Luan F., Wang H., Hu Y., Yang Q. (2020): Synergistic effect: A common theme in mixed-species litter decomposition. *New Phytologist*, 227: 757–765.
- Macdonald S.E., Landhäuser S.M., Skousen J., Franklin J., Frouz J., Hall S., Jacobs D.E., Quideau S. (2015): Forest restoration following surface mining disturbance: Challenges and solutions. *New Forests*, 46: 703–732.
- Mehlich A. (1984): Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis*, 15: 1409–1416.
- Muraškiene M., Varnagiryte-Kabašinskiene I., Stakenas V. (2025): The effect of clear-cut age on soil organic carbon and nitrogen indices in Scots pine (*Pinus sylvestris* L.) stands. *iForest – Biogeosciences and Forestry*, 18: 146–153.
- Nicolescu V.N., Vor T., Mason W.L., Bastien J.C., Brus R., Henin J.M., Kupka I., Lavnyy V., La Porta N., Mohren F., Petkova K., Rédei K., Štefančík I., Wąsik R., Perić S., Hernea C. (2020): Ecology and management of northern red oak (*Quercus rubra* L. syn. *Q. borealis* F. Michx.) in Europe: A review. *Forestry: An International Journal of Forest Research*, 93: 481–494.
- Novák J., Dušek D., Slodičák M. (2014): Quantity and quality of litterfall in young oak stands. *Journal of Forest Science*, 60: 219–225.
- Olorunfemi I.E., Fasinmirin J.T., Akinola F.F. (2018): Soil physico-chemical properties and fertility status of long-term land use and cover changes: A case study in Forest vegetative zone of Nigeria. *Eurasian Journal of Soil Science (EJSS)*, 7: 133–150.
- Park H.J., Park Y.S., Lee S.M., Choi W.J. (2018): Decomposition of pine and oak litters as affected by their lignin and mineral concentrations. *Korean Journal of Soil Science and Fertilizer*, 51: 377–387.
- Pietrzykowski M. (2019): Tree species selection and reaction to mine soil reconstructed at reforested post-mine sites: Central and eastern European experiences. *Ecological Engineering*, 142: 100012.
- Polyakova O., Billor N. (2007): Impact of deciduous tree species on litterfall quality, decomposition rates and nutrient circulation in pine stands. *Forest Ecology and Management*, 253: 11–18.
- Ponge J.F. (2003): Humus forms in terrestrial ecosystems: A framework to biodiversity. *Soil Biology and Biochemistry*, 35: 935–945.
- Ponge J.F. (2013): Plant–soil feedbacks mediated by humus forms: A review. *Soil Biology and Biochemistry*, 57: 1048–1060.

<https://doi.org/10.17221/29/2026-JFS>

- Prescott C.E., Zabek L.M., Staley C.L., Kabzems R. (2000): Decomposition of broadleaf and needle litter in forests of British Columbia: Influences of litter type, forest type, and litter mixtures. *Canadian Journal of Forest Research*, 30: 1742–1750.
- R Core Team (2025): R: A Language and Environment for Statistical Computing. Vienna, R Foundation for Statistical Computing. Available at: <https://www.R-project.org/> (accessed Mar 15, 2026)
- Rautio P., Fürst A., Stefan K., Raitio H., Bartels U. (2020): Part XII: Sampling and analysis of needles and leaves. Version 2020-3. In: UNECE ICP Forests Programme Coordinating Centre (ed.): *Manual on Methods and Criteria for Harmonized Sampling, Assessment, Monitoring and Analysis of the Effects of Air Pollution on Forests*. Eberswalde, Thünen Institute of Forest Ecosystems. Available at: https://www.icp-forests.net/fileadmin/icp_forests/Dateien/Manual_Versions/2020-22/ICP_Manual_part12_2020_Foliage_version_2020-3.pdf (accessed June 22, 2026)
- Ritchie G.S.P., Weaver D.M. (1993): Phosphorus retention and release from sandy soils of the Peel-Harvey catchment. *Fertilizer Research*, 36: 115–122.
- Rothe A., Kreutzer K., Küchenhoff H. (2002): Influence of tree species composition on soil and soil solution properties in two mixed spruce-beech stands with contrasting history in Southern Germany. *Plant and Soil*, 240: 47–56.
- Sheoran V., Sheoran A.S., Poonia P. (2010): Soil reclamation of abandoned mine land by revegetation: A review. *Journal of Soil, Sediment and Water*, 3: 1–20.
- Shepherd M.A., Bennett G. (1998): Nutrient leaching losses from a sandy soil in lysimeters. *Communications in Soil Science and Plant Analysis*, 29: 931–946.
- Speckert T.C., Huguet A., Wiesenberger G.L.B. (2024): Afforestation induced shift in the microbial community explains enhanced decomposition of subsoil organic matter. *EGU-sphere*. (preprint)
- Stuckenberg T., Lu J.Z., Scheu S. (2025): C, N and P dynamics during litter decomposition in pure and mixed beech – conifer stands: Effects of litter species, site conditions and native vs non-native conifer species. *Forest Ecology and Management*, 594: 122929.
- Tóth J.A., Nagy P.T., Krakomperger Z., Veres Z., Kotroczó Z., Kincses S., Fekete I., Papp M., Lajtha K. (2011): Effect of litter fall on soil nutrient content and pH, and its consequences in view of climate change (Síkfőkút DIRT Project). *Acta Silvatica et Lignaria Hungarica*, 7: 75–85.
- Turski M., Korczyński I., Łukowski A., Węgiel A. (2024): Needle biomass turnover rate in Scots pine stands of different ages. *Forests*, 15: 1454.
- Uri V., Kukumägi M., Aosaar J., Varik M., Becker H., Aun K., Nikopensius M., Uri M., Buht M., Sepaste A., Padari A., Asi E., Sims A., Karoles K. (2022): Litterfall dynamics in Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula*) stands in Estonia. *Forest Ecology and Management*, 520: 120417.
- Van Gorp L., Erskine P.D. (2011): The influence of topsoil management on Stradbroke Island sand mine rehabilitation: Implications for ecosystem recovery. *The Proceedings of the Royal Society of Queensland*, 117: 377–389.
- Viewegh J., Kusbach A., Mikeska M. (2003): Czech forest ecosystem classification. *Journal of Forest Science*, 49: 74–82.
- Voltr V., Menšík L., Hlisenikovsky L., Hruška M., Pokorný E., Pospíšilová L. (2021): The soil organic matter in connection with soil properties and soil inputs. *Agronomy*, 11: 779.
- Vor T., Spellmann H., Bolte A., Ammer C. (2015): *Potenziale und Risiken eingeführter Baumarten: Baumartenportraits mit naturschutzfachlicher Bewertung*. Göttingen, Göttingen University Press: 309. (in German)
- Wei X., Yang Y., Shen Y., Chen Z., Dong Y., Wu F., Zhang L. (2020): Effects of litterfall on the accumulation of extracted soil humic substances in subalpine forests. *Frontiers in Plant Science*, 11: 254.
- Weil R.R., Brady N.C. (2017): *The Nature and Properties of Soils*. Columbus, Pearson: 1086.
- Welch B.L. (1951): On the comparison of several mean values: An alternative approach. *Biometrika*, 38: 330–336.
- Woziwoda B., Kopeć D., Witkowski J. (2014): The negative impact of intentionally introduced *Quercus rubra* L. on a forest community. *Acta Societatis Botanicorum Poloniae*, 83: 39–49.
- Young R.E., Gann G.D., Walder B., Liu J., Cui W., Newton V., Nelson C.R., Tashe N., Jasper D., Silveira F.A.O., Carrick P.J., Hägglund T., Carlsén S., Dixon K. (2022): International principles and standards for the ecological restoration and recovery of mine sites. *Restoration Ecology*, 30: e13771.
- Zhang P., Tian X., He X., Song F., Ren L., Jiang P. (2008): Effect of litter quality on its decomposition in broadleaf and coniferous forest. *European Journal of Soil Biology*, 44: 392–399.
- Zhou G., Xu S., Ciais P., Manzoni S., Fang J., Yu G., Tang X., Zhou P., Wang W., Yan J., Wang G., Ma K., Li S., Du S., Han S., Ma Y., Zhang D., Liu J., Liu S., Chu G., Zhang Q., Li Y., Huang W., Ren H., Lu X., Chen X. (2019): Climate and litter C/N ratio constrain soil organic carbon accumulation. *National Science Review*, 6: 746–757.
- Zönnchen C., Schaaf W., Esperschütz J. (2014): Effect of plant litter addition on element leaching in young sandy soils. *Journal of Plant Nutrition and Soil Science*, 177: 585–595.

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