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Edaphic legacy of phosphorus fertiliser in the restoration of the biodiverse Kwongan ecosystem in ultra-low P soils

Vinicius H. De Oliveira [a], Mark P. Dobrowolski [b,c,d], Sarah Duddigan [a,e], Mark Tibbett [a,c,*]

[a] Department of Sustainable Land Management & Soil Research Centre, School of Agriculture, Policy and Development, University of Reading, Reading, Berkshire, UK
[b] Iluka Resources Ltd., Perth, Australia
[c] School of Biological Sciences, The University of Western Australia, Perth, Australia
[d] Harry Butler Institute, Murdoch University, Perth, Australia
[e] Department of Geography and Environmental Science, University of Reading, Reading, UK

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ABSTRACT

The kwongan ecosystem is a biodiversity hotspot on the coastal sandplain of southwest Western Australia. It harbours many rare and endemic plant species adapted to nutrient impoverished soils, particularly to low phosphorus (P). In some kwongan regions surface strip-mining has drastically disturbed these ecosystems, requiring restoration by soil profile reconstruction and re-establishment of the native vegetation, often assisted by mineral fertiliser applications. We examined soil monitoring data from several post-mining sites of restored kwongan vegetation (n = 127), categorised by age groups (10, 20, 30 and 40-year-old sites) and fertilisation history (type of fertiliser applied). Thirty two soil variables were compared to the surrounding native soils (n = 135) by multivariate and univariate statistical approaches to determine whether different restoration ages and fertilisers had long-term impacts on soil physicochemical characteristics. Our analyses showed that restored soils differed from native, with substantially lower carbon (−41 %) and nitrogen (−15 %). Sites restored within the last 10 years had higher sodicity and much lower porosity, while 40-year-old sites presented nearly ten times more Total P. Recent non-fertilised soils showed similar P concentrations to the reference sites, however, older restored soils had a high legacy P, which is a clear consequence of past superphosphate applications, and greatly decreased their N:P stoichiometric ratios compared to native soils. We show that, after decades, restored soils are still impacted by the past mining activities and fertiliser application. These changes will likely alter microbial and plant communities, impairing restoration trajectories towards the native kwongan vegetation, particularly for P-sensitive species. Despite benefits of P-fertilisation (e.g. improved plant cover), the low carbon stocks and N:P ratios indicate a divergent ecosystem from the native state. Such changes in ecosystem stoichiometry may affect plant species competitiveness, and alter the composition of other trophic levels. Adjusting future restoration practices to reduce P fertilisation is promising, but addressing long-term stoichiometric shifts and soil compaction remains crucial.

1. Introduction

The region of southwest Western Australia (WA) is a global biodiversity hotspot for plant species, particularly within vegetation known as *kwongan*, a mediterranean-type shrub ecosystem comparable to the south African *fynbos* and Brazilian *campos rupestres* (Mucina et al., 2014; Oliveira et al., 2015; Tsakalos et al., 2018). Kwongan plant communities in WA have evolved in highly leached and nutrient impoverished soils, mostly sandplains with extremely low phosphorus (P) concentrations (Byrne et al., 2014; Laliberté et al., 2014). Despite these constraints, such conditions promoted an exceptionally high floristic and functional diversity, in which plants developed many nutrient-acquisition strategies, mostly notably towards P uptake (Lambers et al., 2019).

This extremely biodiverse and unique ecosystem has developed over heavy-mineral sands deposits consisting of ilmenite, rutile and leucoxene that formed on early Pleistocene or late Tertiary shorelines at Eneabba, WA (Playford et al., 1976). These mineral deposits are economically valuable sources of the metals zirconium and titanium, and are extracted by surface mining. Surface mining requires clearing of vegetation, removal of soil, which alters the topography and geology

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* Corresponding author.
E-mail address: m.tibbett@reading.ac.uk (M. Tibbett).

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ultimately impacting the physical, chemical and biological properties of mined soils (Shrestha and Lal., 2011; Spain et al., 2015; Tibbett, 2024). Due to this drastic disturbance and heavy machinery use, mined soils tend to be more compacted, with altered pH, with substantial loss in nitrogen (N) and soil carbon (C) (Akala and Lal, 2011; Ganjegunte et al., 2009; Shrestha and Lal, 2011; Ritchie et al., 2021).

Mining companies in WA are obligated to reconstruct post-mining ecosystems to a state analogous to pre-mining activities, often to support previous land uses or the original native vegetation, although criteria to define restoration targets, approaches, and completion outcomes are not standardised, often lacking scientific backing or updating (Daws et al., 2023). 'Rehabilitation' is a term that generally refers to the repair of land disturbed by mining activities, aiming to i) ensure long-term stability of these landforms, ii) prevent pollution to the surrounding environment, and iii) repair the soil capacity in sustaining habitats, biota and ecosystem services (Gastauer et al., 2018; Worden et al., 2024). 'Restoration' implies a more ambitious aim of re-establishing the vegetation and ecosystem structure similar to those present in the local unmined ecosystem (Spain et al., 2015; Worden et al., 2024). At Eneabba, restoration is particularly challenging due to the harsh edaphic conditions and complex vegetation, which are little understood and difficult to propagate (Brooks, 2000).

Mine closure and rehabilitation or restoration strategies are planned prior to the start of mining and, in southwest WA, these techniques have evolved to high standards throughout the decades, with more careful planning being made with topsoil handling and its direct return, soil stabilisation, sourcing native seeds and propagules for revegetation, and fertilisation (Seiser, 2001; Koch, 2007; Dobrowolski, 2014). However, despite being a common practice to boost revegetation, fertiliser applications in post-mining soils have been recently shown to alter soil nutrient stoichiometries and plant competition dynamics; thus, they can promote a very dissimilar floristic structure and diversity to the target native ecosystem (Tibbett et al., 2019; Tibbett et al., 2020).

Some nutrients may persist in soils decades after application, such as P, commonly applied as single superphosphate (SSP) fertilisers (Tibbett, 2010); such persistence of P in soils following mineral fertilisation is commonly referred to as "legacy P" (Zhu et al., 2018). In a jarrah forest site restored after bauxite mining, Daws et al. (2021) verified a long-term effect in the plant communities after 20 years since SSP application, leading to lower recruitment of native species that are adapted to low soil P. The persistence of P was also demonstrated in the restoration of a different bauxite mining site (Spain et al., 2018) and a former agricultural land in WA (Parkhurst et al., 2022), remaining significantly higher after 20 and 10 years, respectively. However, these restored soils were higher in clay and oxides (see Soltangheisi et al 2023) than the ones commonly found under kwongan vegetation, therefore it is possible that such P accumulation may not occur in sandy soils (Kang et al., 2011).

Although the evaluation of restoration success involves many indicators, such as the diversity of fauna and flora communities, ecological processes, soil quality and litter decomposition, much focus is given to biodiversity (Bandyopadhyay and Maiti, 2019). The degree in which post-mining soil attributes can recover is seldom documented, but deserving of greater research attention, given their importance to species filtering in vegetation community assembly (Dobrowolski, 2014).

The availability of soil monitoring data from several restoration sites at the Eneabba mine, located on kwongan sandplains, provides a unique opportunity to investigate *a posteriori* hypotheses on the short and long-term effects of mining and restoration practices on soil physicochemical attributes. Through the analysis of historical datasets, we set out to determine whether different restoration ages and fertiliser history had a long-term impact on physicochemical characteristics of restored soils. We hypothesised that: i) a sequence of decadal timeframes after restoration would shift soil characteristics towards the natural state, similar to that found in undisturbed kwongan soils; and ii) total carbon would increase in restored soils through the decadal sequences, while P contents added via fertilisers would have decreased, achieving similar C:N and N:P stoichiometries found in native soils.

2. Material and methods

2.1. Study site and restoration practices

The study area spans roughly 1,210 km^2 and was situated in the vicinity of Eneabba (280 km north of Perth, Western Australia) within the Geraldton Sandplain biogeographical region (Department of the Environment and Energy, 2017), where Iluka Resources mineral sand mining took place (29.9° S, 115.3° E, Fig. S1). The majority of the area (~80 %) rests on the Eneabba Plain, characterised by low-lying terrain covered by early Pleistocene or Pliocene sand dunes, classified mostly as sand over yellow–brown clay and laterite soils, with average Total N and P of 0.03 % and 19 mg kg^{-1}, respectively (Mucina et al., 2014; Tsakalos et al., 2018). The vegetation of the region largely comprises highly diverse kwongan vegetation, with annual average temperature of 21 °C and rainfall of 490 mm (Bureau of Meteorology, 2017; Riviera et al., 2021).

Compared to other mining types, surface strip mining is shallow and relatively rapid for a given area of land, allowing for the swift replacement of reserved topsoil for restoration purposes (Jones, 2009). At the Iluka Eneabba site, restoration has been undertaken since the 1970 s, in which various management practices have been employed throughout the years, evolving as knowledge developed. These were, but not limited to: topsoil replacement, soil stabilisation using cereal crops, application of mulch and/or inorganic fertilisers before seeding or planting native kwongan species for ecosystem restoration (Riviera et al., 2021). Permanent restoration plots were established at every newly restored site since the 1970 s for the purpose of consistent monitoring by Iluka Resources. While monitoring plots were not designed to be experimental or to test *a priori* hypotheses, we have imposed structure and 'treatments' considering their chronological age and their fertiliser inputs which, due to their history, are not balanced. However, restored plots shared enough similarities to allow a systematic categorisation of data based on their Age (establishment year) and Fertilisation history (type and amount of fertiliser applied), and test our *a posteriori* hypotheses as a 'found experiment'.

2.2. Soil sampling and categorisation by age and fertiliser history

Topsoil samples were collected by augering (0 to 20 cm) in 314 different plots, of which 187 belonged to 'Native' reference sites (sampled in 2014/2015 austral summer), and 127 belonged to 'Restoration' sites (sampled in 2015/2016 austral summer), spanning decades since their establishment, from 1979 to 2012. Due to this time variation, soils from restored sites were grouped into four categories, referred to here as 'Age groups', each comprising a decade range since restoration began: '10′ (0 to 10 years), '20′ (11 to 20 years,), '30′ (21 to 30 years), and '40′ (31 to 40 years). We opted to use a discrete categorisation, because these ranges roughly reflect the different management practices that changed throughout the years. For instance, in the older sites, when restoration began three to four decades ago, superphosphate (SSP) fertilisers were mostly applied together with the seed mix, while more recent sites mainly received slow releasing P fertilisers, high N-fertilisers or no fertilisers at all (Table S1).

Indeed, the fertilisers applied during rehabilitation were not consistent across all sites at the Eneabba area, and they vary depending on the year each restoration site was established. To promote plant growth and soil stabilisation, different fertilisers have been added at the time of sowing and, in some cases, along with some previously fertilised topsoil reclaimed from rehabilitated sites disturbed by mining a second time. Therefore, to investigate our hypotheses on the effects of fertilisation on long-term soil characteristics (e.g. Total P, N and C) we have grouped these different fertilisers into four general categories: 'No fertilisation', 'Apex + Gusto', 'CropRich' and 'Super' (Table 1), after preliminary analyses of variance (Table S1).

We have relied as much as we could on records kept throughout the years and, based on each fertiliser applied and their respective amounts, we have estimated the overall P and N inputs (kg ha^{-1}) into the topsoil. It is important to clarify that fertilisation history do not correspond exactly to Age groups, as some fertilisers have been used in both recent and older sites (e.g. superphosphate). In addition, some sites were also fertilised (to establish a crop in the subsoil to stabilise against erosion) before receiving the topsoil; these occasional subsoil fertilised sites ($>$ 20 cm in depth) were initially considered as a subset category, but preliminary statistical analysis showed subsoil fertilisation had no effects on topsoil chemical characteristics. Therefore, for our purposes in this study, subsoil fertilisation was not considered as a separate factor.

2.3. *Soil analyses*

Physical and chemical properties of all soil samples were analysed by various methods, as previously described in Tsakalos et al. (2018), including soil texture, bulk density/porosity, electrical conductivity (EC), exchangeable sodium percentage (ESP), pH, Total P, N, and C, exchangeable cations, and available ions via Mehlich 3 (M3) extraction. Here, Total C is mostly comprised of soil organic carbon, as no inorganic carbonates were detected after a fizz test (Rayment and Lyons, 2011). A total of 32 soil variables were compiled and used for the following ordination and statistical analyses (Table S2).

Soil availability of different nutrients was also measured by PRS® (Plant Root Simulator) resin probes (Western Ag Innovations, 2010), which capture elements present in the soil solution, and have been shown to provide reliable results in the field (Parkhurst et al., 2022). These probes are comprised of cation or anion exchange membranes framed by a plastic stake, which are buried in the soil surface and left to absorb nutrients from the soil solution during a certain period. Here, four anion and four cation stakes were buried vertically in the topsoil ($<$ 15 cm) of different native (n = 20) and restored sites (n = 24). After 28 days (July to August 2022), PRS probes were retrieved, washed with deionised water and returned to the manufacturer for analysis (Western Ag Innovations Inc., Saskatchewan, Canada). PRS® results include: nitrate (NO_3), ammonium (NH_4), magnesium (Mg), calcium (Ca), potassium (K), sulphur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), aluminium (Al), P and lead (Pb).

2.4. *Statistical analyses*

In order to compare soils with similar textural characteristics, a ternary plot was constructed using data for clay, sand and silt contents of 187 native and 127 restored sites (Fig. 1). All restored soils presented $>$ 90 % sand and $<$ 10 % clay contents, which influence many other edaphic characteristics, e.g. porosity, ECEC, nutrient availability. Therefore, all native soils with unmatching textural classes (i.e. $\geq$ 10 % clay, or $\leq$ 90 % sand) were excluded from all analyses, leaving a remaining total of 135 native sites.

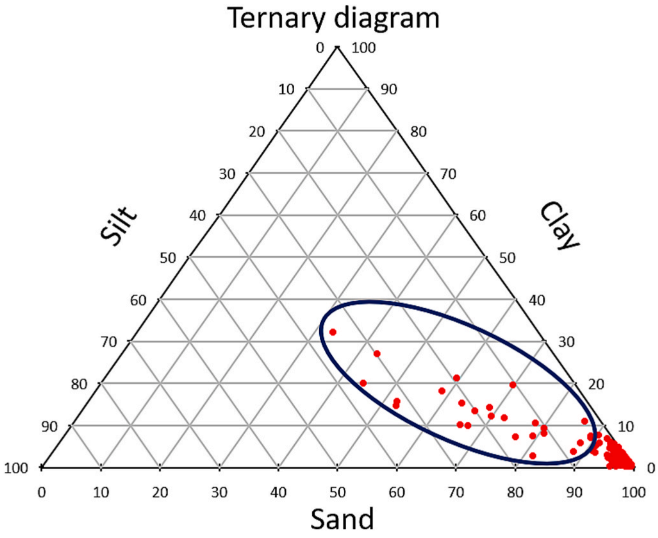

Fig. 1. Ternary plot for the soil texture (proportion of sand, silt, and clay) of all native and restored sites. Ellipses show the samples with the highest clay/silt contents (all from native soils), which were then removed from the dataset before further analyses.

Prior to analyses, data was transformed by log(x + 1) and z-scored normalised to render the 32 variables (Table S2) in the same scale (Legendre and Legendre, 2012; Tripathi and Singal, 2019; Dago et al., 2021). Principal Component Analysis (PCA) was carried out in the transformed data set using all variables, but further reduced to nine variables that explained the most data variability. The multivariate distribution of these soil characteristics was captured by a Euclidean distance matrix, which was further used for the PERMANOVA, with 9999 permutations for main effects and pairwise tests (Anderson, 2001). The PERMANOVA factors were either: Site (Native, Restoration) or Age group (Native, 10, 20, 30 and 40-year old plots). Age groups are based on ranges between the restoration start year and the soil sampling in 2016, in which 10: 0 to 10 years (n = 47); 20: 11 to 20 years (n = 47); 30: 21 to 30 years (n = 20) and 40: 31 to 40 years (n = 13).

A metric multidimensional scaling (mMDS) of bootstrap averages was carried out to better visualise the distances among Age groups (100 simulated samples), in the Euclidean space. The bootstrap averaging process is based on repeated resampling (with replacement; 100 iterations) of the original dataset in each Age group; these average values can be thus visualised in a mMDS, using as many dimensions as needed to match the original distance matrix (a high correlation coefficient of *rho* = 0.991); in this case m = 8 dimensions were needed to reach the final ordination (Adams et al., 2016; Balazy et al., 2021). The distances displayed in the mMDS were corroborated by PERMANOVA, $p < 0.001$

Table 1
Fertiliser categories defined after grouping plots with similar fertilisation history across all restored sites. These include fertiliser types and brands, and the estimated P and N inputs[1] on post-mining topsoil (kg ha^{-1}) at the start of the restoration process.

Fertiliser category	Products applied across different sites	Estimated P input	Estimated N input	Rehab ages	Number of sites
		kg ha^{-1}		years	
No fert.	no application	0	0	7–13	37
Apex + Gusto	Apex low P + Gusto (Summit Fert.)	6.8	21	4–5	17
CropRich	CropRich CropRich + P fertilised topsoil	9.0	17	14–19	27
Super	Single superphosphate (SSP) SSP + Cu, Zn, Mo SSP + Cu, Zn, Mo + Agran + Potash Coastal superphosphate	8.7	5	7–37	46

[1] Estimation of P and N inputs were based on the amount and type of fertilisers applied, as obtained by Iluka Resources, and their percentages as informed in the product labels and See supplementary Table S1 for more information.

(Clarke et al., 2014). Next, similarity percentages analysis (SIMPER) was used to discriminate the contribution of each variable (%) to the separation between different Sites or Age groups (Balazy et al., 2021).

Univariate PERMANOVA was also performed for some of these variables (9999 permutations, at 5 % significance level), with factors being Site, Age group, or Fertiliser type (Table 1). All ordinations, multivariate and univariate PERMANOVA analyses were performed using the software Primer-e v7 with the PERMANOVA + add-on (Anderson et al., 2008; Clarke and Gorley, 2015).

3. Results

3.1. Overall differences between native and restored soils

PERMANOVA detected significant differences between native and restored soils in the multivariate dataset ($p < 0.001$) (Fig. 2), and SIMPER analysis pinpoints the main variables responsible for this difference (Table 2).

PCA using nine variables – ESP, porosity, Al (M3) and Pb (M3), Total P, Total N, Total C, C:N ratio, ECEC – was able to capture 64 % of the data variation with PC1 (40 %) and PC2 (24 %), while PC3 only accounted for 9.4 % (Fig. 2). Clear relationships are displayed between restored sites and Total P, Pb (M3), Al (M3), and ESP, while native sites contain soils positively correlated with Total C, N, porosity and ECEC.

We carried out a univariate PERMANOVA to test for differences between sites, for specific variables of interest such as Total P, Total C, C:N ratio and porosity (Fig. 3). The biggest contrast is seen in Total P, which is overall 79 mg kg^{-1}, almost triple of what is found in native soil in this region, of 28 mg kg^{-1} (Fig. 3a). Despite high soil P, restored soils have low Total C (by 41 %), Total N (by 15 %) and, consequently, in C:N ratio (by 32 %) in comparison to native soils (Fig. 3b, 3c, 3d). Conversely, there is evident increase in ESP (by 163 %) and, surprisingly, available Pb (M3) (by 38 %) in restored soils (Fig. 3e, 3 g). Lower porosity is also evident, indicating higher soil compaction in relation to native sites (Fig. 3h).

3.2. Variation in soil characteristics by restoration age

Post-mining restoration in these sites did not occur within the same period, some started in 1979 and early 80′s, while the most recent sites began the process in 2012. Because of this time variation, we have decided to split the data into different Age groups, to verify the response of these variables at different times. In addition, each Age group is more or less associated with contrasting fertilisation practices, which will be explored later. A PERMDISP test (permutational test of multivariate dispersions) was carried out to compare the variation in structure across the different Age groups in terms of their physicochemical characteristics (Anderson et al., 2008), and no difference in variability patterns were found among all groups (9999 permutations, $p > 0.05$).

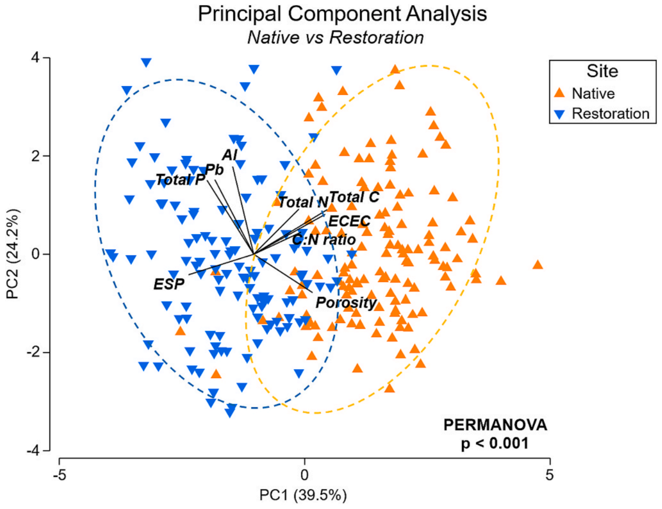

Fig. 2. Principal component analysis (PCA) using nine soil variables from native (n = 137) and restored (n = 127) sites. Ellipses represent the significant difference between the groups according to PERMANOVA ($p < 0.001$; R^2 = 0.18). ESP: exchangeable sodium percentage, Pb: available M3, Al: available M3, ECEC: effective cation exchange capacity.

Table 2
Results of the SIMPER analysis with 19 variables with the highest contribution towards differences between native and restored soils, and their percentage of contribution.

Variable	Average square distance between groups	Contribution (%)	Cumulative (%)
ESP	3.2	7.2	7.2
ECEC	3.0	6.8	14
Total C	2.9	6.6	21
Porosity	2.8	6.3	27
available Ca (M3)	2.7	6.2	33
Total P	2.4	5.4	38
available Fe (M3)	2.3	5.2	44
C:N ratio	2.2	5.0	49
available Zn (M3)	2.1	4.9	54
Total N	2.1	4.9	58
available Pb (M3)	2.1	4.8	63
available Na (M3)	2.0	4.7	68
available S (M3)	2.0	4.7	73

Multivariate PERMANOVA using Age group as a factor (Native, 10-, 20-, 30- and 40-year-old sites), showed that each group was different from one another after pairwise post-hoc tests ($p < 0.001$). The only exception were the soils from 30 and 40-year sites, which are slightly similar, with a weak p-value of 0.058. To better visualise these pairwise differences, an mMDS using bootstrap averages was generated, in which each group is resampled multiple times to create a cloud of simulated samples (Fig. 4a). We can observe distinct distances among all Age groups, except between 30 and 40-year sites, as detected by PERMANOVA.

It also becomes clear that the groups most distant from the native reference were the 10- and 40-year-old restored sites (Fig. 4), but due to different reasons. Indeed, SIMPER analysis showed that the variables mostly contributing to the distance between native and 10-year-old sites were: porosity (10 %), ESP (8 %) and ECEC (8 %). While between the native and 40-year sites, the highest contributing variables were: Total P (15 %), available Pb (11 %) and porosity (6 %).

Bubble plots were generated upon the PCA (on averaged values) to illustrate the contrasting variables among Age groups (Fig. 4b, 4c). It becomes apparent that N is highest and P is lowest in native soils, a ratio that has been inverted in 30- and 40-year old restored soils (Fig. 4b). Similarly, the high porosity and low ESP values also shift from native to restored soils, most notably at the 10-year-old site, which is strongly associated with high ESP and low porosity (Fig. 4c). Bubble plots for Total C, soil density and C:N ratio can be found in Fig. S2.

PERMANOVA was then carried out to confirm the differences in Total P, N and C, C:N and N:P ratios and ESP (%) among the Age groups, including the native soils as reference values (Fig. 5). All restored soils contained significantly more Total P than native soils (Fig. 5a), especially in 30- and 40-year-old sites (> 100 mg kg^{-1}). Total N and Total C had little variation among age groups, but were all lower than in the native soils (Fig. 5b, 5c). There is a noticeable shift in N:P ratios, decreasing by almost half from native soils to 10- and 20-year-old soils, and by 3-fold in 30- and 40-year-old sites (Fig. 5e). While ESP was much

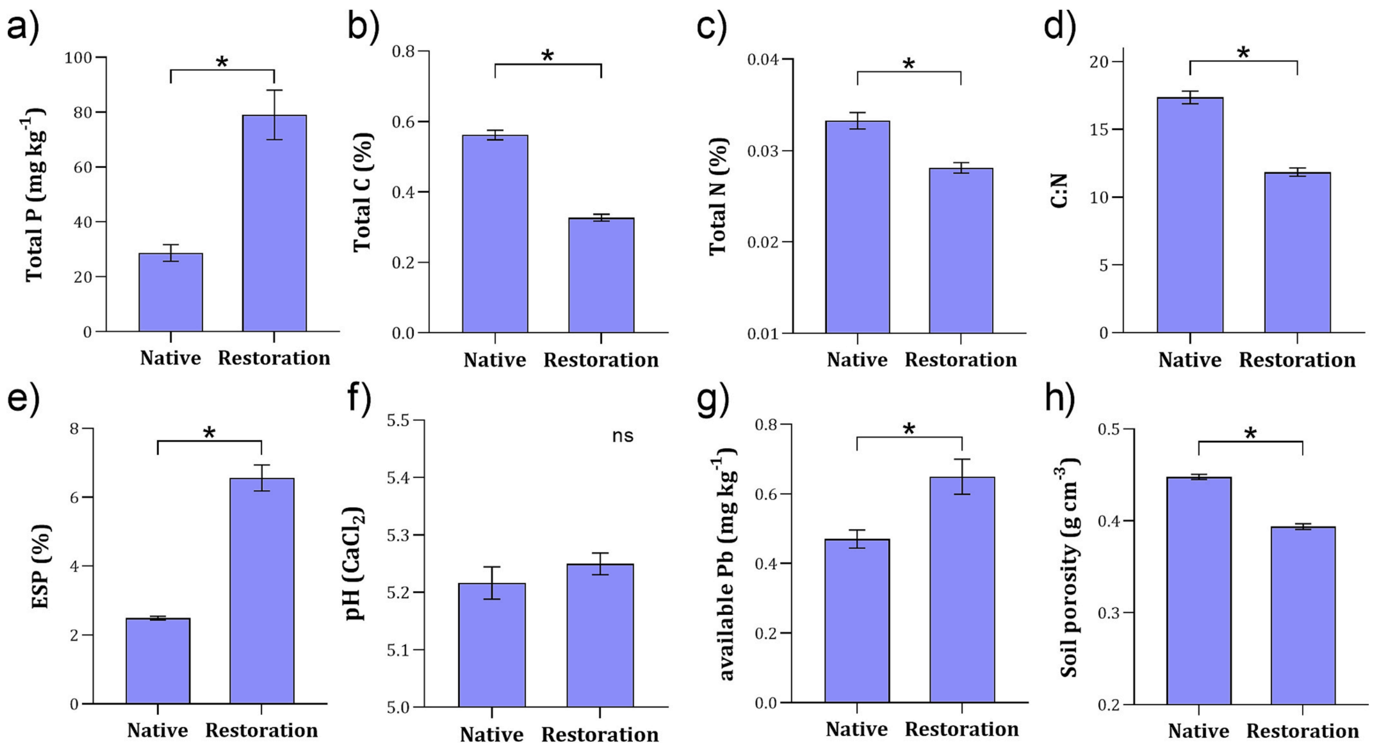

Fig. 3. Comparison of different soil variables between native and post-mining restoration sites. Bars are means of 137 (native) and 127 (restoration) samples, accompanied by (+/-) standard errors. Asterisks indicate significant difference determined by One-way PERMANOVA ($p < 0.001$). ns: not significant.

higher in all restored sites, tending to decrease in older soils (Fig. 5f).

3.3. *Effects from fertilisation history*

It is important to consider that Age is not the only factor behind contrasts in soil variables among the different restored and native sites. As mentioned previously, different fertilisers were applied throughout the years at the start of the rehabilitation process (Table 1). Sites that began restoration 30 and 40 years before the sampling in 2016, were treated with different types of SSP fertilisers (Super), while more recent sites were either not fertilised, or treated with Crop Rich or Apex + Gusto fertilisers. Thus, differences in Total P, N, C and available Pb (M3) due to the fertilisation history were assessed by PERMANOVA, and their comparison with native soils are presented in Fig. 6.

Although non-fertilised soils had similar Total P to native soils (Fig. 6a), the other restored soils had significantly higher Total P, especially those that received SSP fertilisers. Soils fertilised by SSP have a mean of 150 mg kg^{-1}, approximately five times higher than in native undisturbed soils (~30 mg kg^{-1}) (Fig. 6a). However, despite fertilisation, most restored soils still presented much lower Total N and C, compared to native sites (Fig. 6b, 6c). The levels of available Pb (M3) were also investigated as it was found to be highly correlated to Total P in older restored sites (Fig. 2). It became clear that high Pb only occurs in soils that received Super fertiliser (Fig. 6d), while other restored sites presented lower levels, similar to native soils.

Despite the overall higher Total P contents found in restored soils, plant root simulator (PRS probes) showed that soluble P was still comparable to native soils (Table 3). In terms of overall availability (i.e. P in soil solution), “Super” fertilised soils presented higher concentrations of most elements in comparison to native soils. Contrarily, all nutrients in soils fertilised with “Crop Rich” presented the same availability as the native soils (Table 3).

4. Discussion

In general, restored sites presented different soil physicochemical characteristics when compared to native soils, and SIMPER analysis indicated which are the main variables accounting for this difference. We expected that such differences would be associated mostly with the newly restored sites, which are still in early stages of restoration, as we hypothesised that a timeframe of three to four decades should decrease these multivariate dissimilarities, bringing older soils closer to natural levels. However, this was not the case and both older and 10-year-old restored sites were equally distant from the native soils, as seen in the mMDS plot (Fig. 4). Although SIMPER analysis showed that their dissimilarities to native soils are due to different reasons: while soils that have been under rehabilitation within the last 10 years had lower porosity, ECEC and much higher sodicity than natural soils, older soils (> 20 years) had considerably more Total P. These contrasts will be discussed considering both the restoration timeframe (Age groups) and their associated fertilisation history (Fertiliser groups).

4.1. *Higher levels of compaction and sodicity were found in restored sites*

All restored soils presented lower porosity (i.e. higher density) than native soils (Fig. 3h), but especially in the 10-year-old sites (Fig. 4c). This was expected, as the use of heavy machinery and the sand extraction process during mining are known to promote soil compaction and hardening, decreasing soil porosity and water retention (Croton and Ainsworth, 2007; Schaffer et al., 2008; Ritchie et al., 2021). Although porosity and infiltration rate may improve with plant colonisation (Lardner and Tibbett 2013; De Jong et al 2015) and with increasing organic carbon contents (Schaffer et al., 2008), compaction may be a long-lasting effect, as verified in an oak forest soil 85 years after reclamation (Twum and Nii-Annang, 2015) and in the present work (Fig. S3). This is especially true for sandy soils, such as in the present work, which are less resilient and harder to recover once compacted in comparison to soils richer in clay (Huang and Hartemink, 2020).

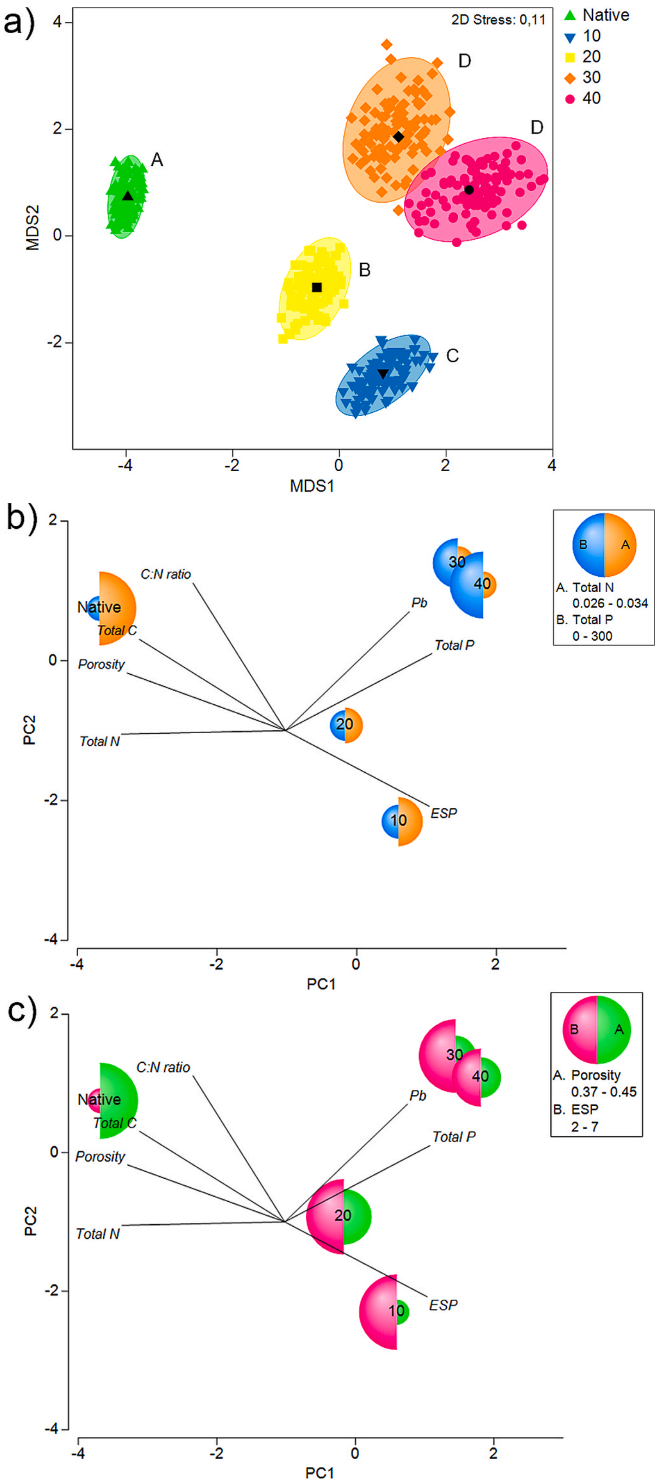

Fig. 4. a) Bootstrap average mMDS plot using 32 variables of different post-mining restored soils, categorised by age groups (native, 10-, 20-, 30- and 40-year-old sites), based on a Euclidean distance matrix. Different uppercase letters represent significant distances among groups, determined by PERMANOVA ($p < 0.001$; $R^2 = 0.24$). b) and c) Bubble plots based on a PCA with 32 variables averaged by Age groups: Native, 10-, 20-, 30- and 40-year-old restored sites. Total N (%) and Total P (mg kg^{-1}) are shown in orange and blue, respectively (b). Porosity (g cm^{-3}) and ESP (%) are shown in green and pink, respectively (c). Bubble sizes correspond to the ranges within each variable scale, vectors show the most contributing variables. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Sodicity is the presence of high proportion of sodium ions in relation to other cations adsorbed to soil particles, with ESP above 6 % being considered sodic in Australian soils (Shaw et al., 1994). All restored sites were slightly sodic, with ESP between 6 and 7 %, while in native soils, ESP average was only 2.5 %. This may have resulted from the process of topsoil removal and replacement after surface mining (Riviera et al., 2021). In this case, deeper soil layers could have been brought up to the surface enriching the restored topsoil with sodium, as ESP was shown to be higher in subsoils of southern Australian (Naidu et al., 1993).

Both soil compaction and sodicity are important factors because they can affect plant development and physiology, such as root growth and water absorption, besides deteriorating soil structure (Huang and Hartemink, 2020; Stavi et al., 2021). These may influence plant–plant interactions during restoration, decreasing the competitiveness and establishment of native vegetation (Bassett et al., 2005; Lardner and Tibbett, 2013). For instance, *Beaufortia squarrosa* (Myrtaceae) is an endemic species from Western Australian that prefers well-drained and porous soils (Smith et al., 2023), becoming weak competitors in compacted conditions.

4.2. *Total P remains high in restored soils decades after fertilisation*

The main reason that restored soils were overall significantly different from the native reference is because of their much higher Total P concentration (Figs. 2, 3a), primarily in 30- and 40-year-old sites, which received different formulations of SSP fertilisers (Fig. 6a). Application of inorganic fertilisers is a common practice in new post-mining restoration sites, as means to enhance initial vegetation cover, increasing soil stabilisation and reducing erosion (Zhang et al., 2015; Tibbett et al., 2020).

In Western Australian soils in particular, P is often the target nutrient supplied via fertilisation, as it can be critical for vegetation establishment and early growth (Koch, 2007; Spain et al., 2015; Tibbett et al., 2020). Indeed, P is frequently a limiting nutrient in many agricultural and natural ecosystems, as phosphate ions generally present low mobility in soils, particularly in acidic conditions, where it can quickly form insoluble complexes with Fe and Al (hydr)oxides (Lynch and Brown, 2008). Thus, as post-mining restoration practices first started in these sites in 1979, it seemed reasonable to provide higher P inputs. However, recent findings highlight the need for caution when applying fertilisers during post-mining rehabilitation (Tibbett et al., 2019). For instance, Total P has been shown to increase and remain higher than the natural reference in a post bauxite mining site (0–10 cm layer, 22 % clay) after 26 years (Spain et al., 2018). Similarly, in jarrah forests that have been established after mining, significant P enrichment was reported after a two-decade field experiment as consequence of superphosphate fertilisation (Daws et al., 2021; Walters et al., 2021). Available P was also shown to remain four times higher after ten years in a rehabilitated agricultural soil in comparison to a woodland reference (Parkhurst et al., 2022).

Here we demonstrate a similar case in all post-mining soils sampled: while non-fertilised soils had statistically similar Total P levels as the native reference, those fertilised by SSP presented much higher Total P, even after three to four decades. We can assume this surplus Total P found in 30- and 40-year-old sites comprised mostly non-soluble P, as PRS probe results suggest little change in solution P in relation to native soils (Table 2). Such low P availability—despite increasing Total P—agrees with findings from Herath and Lamont (2009), who analysed soils from three of our restoration plots (matching the 30-year-old plots), and it is possibly because of the high reactive iron concentrations found in restored soils, leading to higher P immobilisation and persistence.

Considering the sandy nature of these soils (> 90 % sand), we expected eventual leaching/loss of P throughout the decades, especially within the early years, as a consequence of sand permeability (Kang et al., 2011; Spain et al., 2018). Nevertheless, we show here that during the restoration process, high P accumulation can occur in sandy soils as

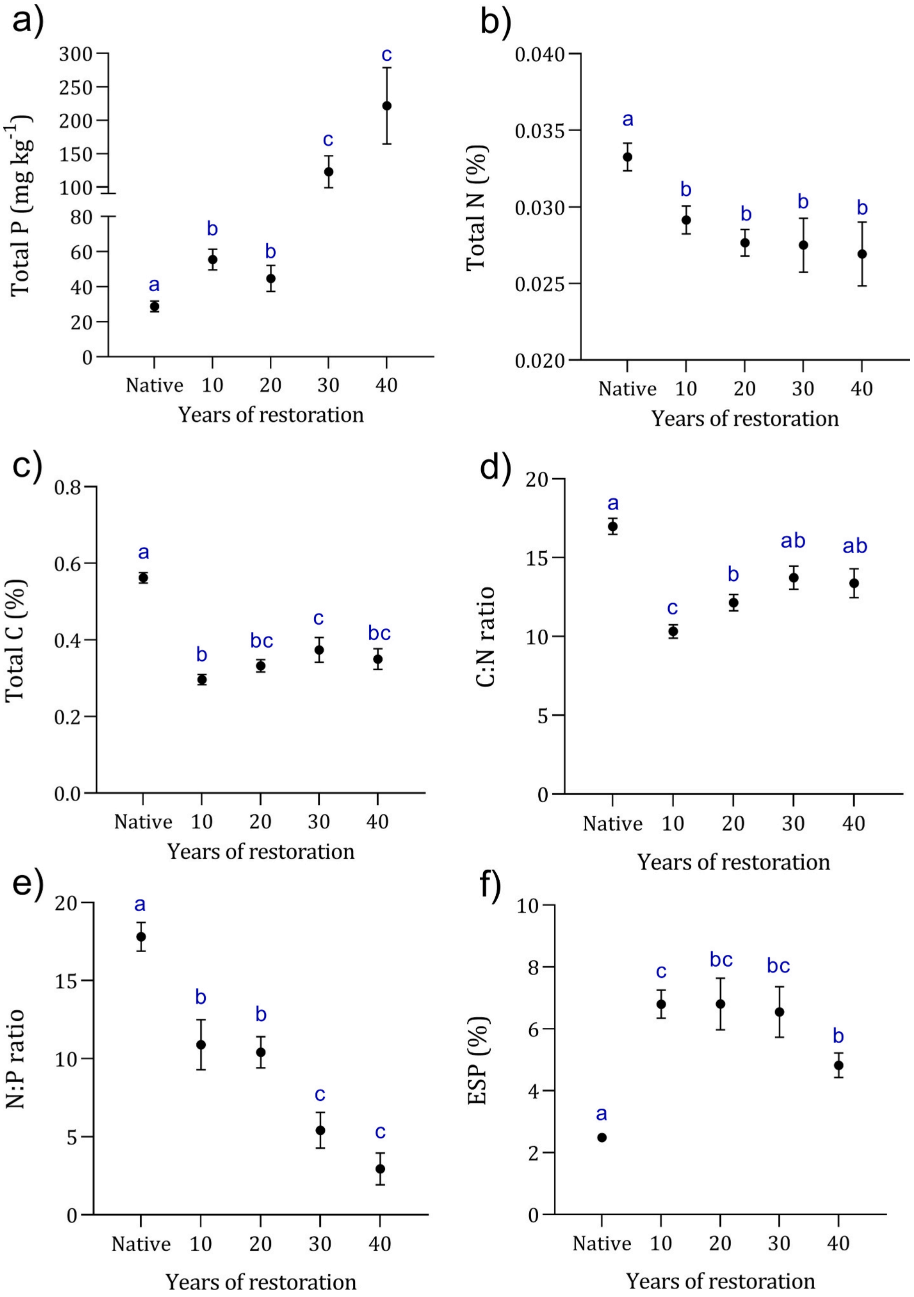

Fig. 5. a) Total P, b) Total N, c) Total C, d) C:N ratio, e) N:P ratio, and f) exchangeable sodium percentage (ESP) in native and post-mining restored sites, categorised by age groups (after 10, 20, 30 and 40 years of restoration). Different letters correspond to significant differences after PERMANOVA pairwise comparisons (9999 permutations, $p < 0.05$).

much as in other soil types, such as richer in weathered clay and oxide minerals (Spain et al., 2018; Daws et al., 2021; Parkshurst et al., 2022). In fact, P retention index (PRI) has been associated with higher clay percentage and exchangeable Ca (Ige et al., 2007), both of which were very low in the restored soils from our study. Recent evidence suggests a significant proportion of P in sandplain soils is held in organic forms (Zhong et al., 2025), and it is possible that fertiliser P has been metabolised into stable organic species. We also found that Total P had a positive correlation with Al (Spearman, $r_s = 0.49$) and clay contents ($r_s = 0.39$) in restored sites, suggesting co-precipitation with Al (hydr)oxides as contributing factor to P retention (Lynch and Brown, 2008), especially as pH remained low (Fig. 3). Indeed, elevated Fe or Al contents have been linked to higher P retention, even in sandy soils, especially due to low water soluble SSP fertilisers (Ritchie and Weaver, 1993).

What also differentiates our findings from other reports on P persistence in restored sites, is the contrast between what is considered a ‘low’ Total P concentration. For example, it has been estimated that Total P in Australian topsoil is generally low, being around 550 mg kg^{-1}, with values in mining areas ranging between 170 to 480 mg kg^{-1} (Spain et al., 2015; 2018). However, in the native soils of kwongan sites, we verified an average of 29 mg kg^{-1} of Total P, which is exceptionally below the aforementioned range. This highlights the uniqueness of the kwongan ecosystem, and its likely sensitivity to soil P accumulation, as over 50 mg kg^{-1} Total P may hinder some plant species (Lambers et al., 2014).

High persistence of P has major implications for the restoration process if the goal is to reinstate the original vegetation community prior to mining (Tibbett et al., 2020), especially in distinctive environments such as the kwongan. The kwongan flora is known to harbour several

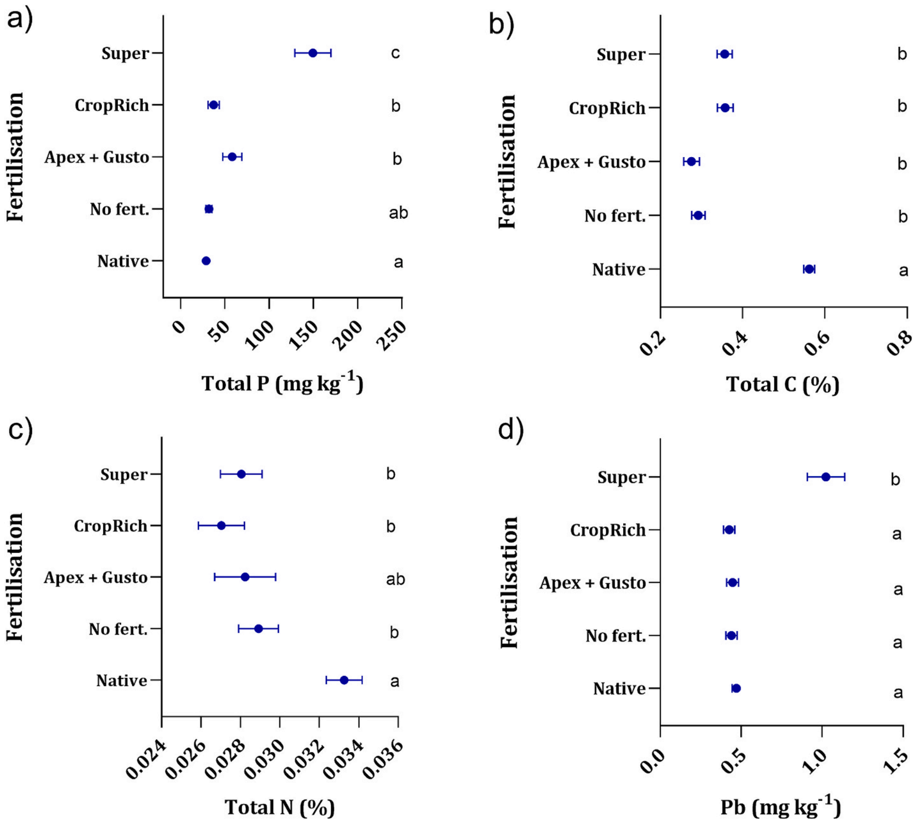

Fig. 6. a) Total P, b) Total C, c) Total N, and d) available Pb (M3) in native and post-mining restoration sites treated with different fertilisers. Different letters correspond to significant differences after PERMANOVA pairwise comparisons (9999 permutations, $p < 0.05$).

Table 3

Nutrient and metal availabilities determined by PRS probes in native and post-mining restoration soils treated with different fertilisers. Values are means with (+/-) standard errors[1]. The letters represent differences between fertiliser types, for each element (Univariate PERMANOVA, $p < 0.05$).

Availability (μg 10 cm^{-2})	Native	No fertilisation	Crop Rich	Super
P	0.11 ± 0.0	0.16 ± 0.1	0.21 ± 0.1	0.12 ± 0.0
NO_3	**9.9 ± 0.8 a**	**5.6 ± 0.9b**	**8.9 ± 0.1 ab**	**6.9 ± 1.0b**
NH_4	18 ± 1.8	18 ± 4.5	14 ± 2.7	23 ± 3.7
Mg	**58 ± 3.6b**	**91 ± 31 ab**	**63 ± 8.2b**	**95 ± 8.6 a**
Ca	170 ± 8.3	180 ± 32	190 ± 8.6	190 ± 11
K	77 ± 5.7	100 ± 28	77 ± 21	120 ± 9.2
S	19 ± 1.3	28 ± 9.2	20 ± 14	30 ± 3.1
Fe	**3.0 ± 0.3b**	**4.4 ± 0.5 a**	**3.1 ± 2.5b**	**4.6 ± 0.5 a**
Mn	**0.58 ± 0.1b**	**0.92 ± 0.3 ab**	**0.61 ± 0.8b**	**1.3 ± 0.2 a**
Zn	**1.6 ± 0.2 a**	**3.7 ± 1.1b**	**1.2 ± 0.3 a**	**1.4 ± 0.1 a**
Cu	**0.09 ± 0.0b**	**0.15 ± 0.0 a**	**0.08 ± 0.3b**	**0.15 ± 0.0 ab**
Al	6.9 ± 0.4	7.4 ± 0.4	6.2 ± 0.0	8.7 ± 0.6
Pb	**0.40 ± 0.1b**	**0.37 ± 0.1b**	**0.21 ± 0.1b**	**1.2 ± 0.3 a**
pH ($CaCl_2$)	**5.4 ± 0.05 a**	**5.4 ± 0.03 a**	**5.1 ± 0.03b**	**5.1 ± 0.03b**

[1] – Native, n = 20; None, n = 7; Crop Rich, n = 4; Super, n = 11.

rare, endemic and threatened species, of which many are sensitive to even slight increases in P, such as some species from the Proteaceae, Myrtaceae and Haemodoraceae families (Lambers et al., 2013; Coates et al., 2014; Tibbett et al., 2019; Williams et al., 2019; Albornoz et al., 2021; Tibbett et al; 2022). Plant sensitivity to P is associated to their limited regulation of P uptake, which can lead to chlorosis, necrosis and stunted growth (Shane et al., 2004; Shane and Lambers, 2006).

Some proteaceous and others taxa that form cluster roots might be even more susceptible to P toxicity in these older restored sites. Cluster roots are morphological root adaptations that release large amounts of carboxylates and phosphatases into the rhizosphere to mobilise P from soils with low availability (Lambers et al., 2011; Lambers et al., 2013). Consequently, because these restored soils have higher Total P, but not necessarily available P, these plants could still be triggered to develop its cluster roots (Wang et al., 2006), being exposed to an 'untapped' and potentially toxic source of P.

Conversely, many other species will likely benefit from high P inputs. One of the most comprehensive long-term studies of P fertilisation for the restoration of P-impoverished soils showed that this practice favoured the growth of weeds and ephemeral species, while zero P application was beneficial to smaller, slow growing species (Daws et al., 2021).

4.3. *Contrasting soil resource stoichiometries*

The stoichiometry of essential resources in the environment (e.g. C, N and P) is considered a major selection pressure in the evolution of plants and its associated microbiota, such as by influencing biomass allocation patterns to forage for a limiting nutrient (Johnson 2010). Naturally, soil C and N derive mostly from litter inputs, while P relates to pedological processes and different bedrock compositions (Lu et al., 2023). Soil C:N:P stoichiometry can influence ecosystem functions, net primary production, microbial communities and biogeochemical cycling (Peñuelas and Sardans, 2022 Sun et al., 2022). Therefore, changes in ecosystem stoichiometry may not only affect plant species competitiveness, but also alter the composition of a different trophic level (i.e. herbivores) resulting from different stoichiometries in plants (Sardans et al., 2012).

Our results show that restored sites present a steep decrease in N:P ratios in comparison to native soils (Fig. 5e). Although N has been added in some cases along with P fertilisation, its behaviour in soils is entirely different, being highly mobile and easily available for plant uptake or loss by leaching (Sardans et al., 2012; Schröder, 2014), therefore, N did not accumulate over time, remaining lower than in natural soils. In a recent *meta*-analysis using 1413 paired observations, it was shown that P additions significantly decrease C:P and N:P ratios in soil, plant, and microbial biomass, but with negligible effects on C:N ratios, potentially impacting ecosystem functions (Sun et al., 2022).

High soil N:P ratio is associated with heathlands and shrublands in Australia (Bui and Henderson, 2013), while lower N:P ratios favours the growth of N-fixing leguminous plants, which are responsive to increasing soil P and still capable to thrive when soil N is low (Daws et al., 2015; Schmidt et al., 2023). Therefore, we expect that plant communities in restored sites will diverge from the low-P adapted kwongan community, as these species have weak competitiveness against N-fixing legumes (Daws et al., 2019; Daws et al., 2021). In fact, this balance between N and P uptake may even be more delicate for some kwongan species such as *Melaleuca seriata* (Myrtaceae) and *Banksia attenuata* (Proteaceae), which display restraint in nitrate uptake and storage, believed to be an adaptation to P-impoverished soils, becoming more responsive to lower N:P ratios (Liu et al., 2022).

Some P-sensitive species may rely on arbuscular mycorrhizal symbiosis to delimit P uptake and not suffer from toxicity, as verified in *Eucalyptus marginata* (Tibbett et al., 2022). However, decrease in soil N:P ratio, as observed here, can decrease mycorrhizal growth response in plants and alter mycorrhizal communities (Qin et al., 2024). Considering that mycorrhizal colonisation and plant response vary with fungal species (Marro et al., 2022), we expect that alterations in microbial communities and colonisation responses will also influence the vegetation in restored sites.

Mining drastically decreases organic matter, and newly reclaimed soils tend to present much lower C and N levels than undisturbed sites (Shrestha and Lal, 2011), all of which are expected to increase with time, especially after afforestation, which improves soil C and CEC as vegetation and litter accumulation develops (George et al., 2010; Li et al., 2024). Indeed, here we show a slight positive trend in Total C in older restored soils (Fig. 5c), however, these levels are overall much inferior than expected, with the highest average (30-year-old sites) still being 33 % lower than native soils. Although this finding is concerning, similar observations have been reported for a restored agricultural soil after 10 years or 26 years after reforestation (Harper et al., 2012; Parkhurst et al., 2024), as well as for an 18-year old restored heathland, which presented 50 % less soil C than the surrounding undisturbed heathlands (Duddigan et al., 2024).

Here we observed increasing C:N ratios in 30 and 40-year-old soils, suggesting higher decomposition and organic matter turn-over compared to newly restored sites (Bui and Henderson, 2013). As Total N levels were similar across all restored sites, we can assume that with time, vegetation development and litter accumulation are responsible for raising C:N (Lu et al., 2023). These results are in agreement with the *meta*-analysis carried out by Sun et al. (2022), showing that P addition on terrestrial ecosystems decreases soil N:P ratios, but present little impact on C:N. Although it may be reassuring to find C:N ratios approaching natural values in these older restored soils, decades of low C:N and higher P levels are expected to influence both vegetation and mycorrhizal community patterns (Albornoz et al., 2023).

4.4. Pb input and persistence in restored soils

We were surprised to detect more Pb (M3) in older restored soils, which was eventually associated with the SSP fertiliser applied in these sites (Fig. 6d). Unlike potassium and nitrogen, phosphate fertilisers tend to present heavy metal contaminants, such as arsenic (As), cadmium (Cd) and Pb. According to Jiao et al. (2012), commercial phosphate fertilisers can harbour Pb concentrations of up to 234 mg kg^{-1}, with an average of 30 mg kg^{-1} for products commercialised in China. Superphosphates from different Sri Lanka regions were reported to contain metal concentrations (in mg kg^{-1}) of up to 10,113 for Al, 46.1 for Cd, 364 for uranium (U) and 80.2 for Pb (Dissanayake and Chandrajith, 2009). However, the average Pb available levels here (1.1 mg kg^{-1}) are low in terms of phytotoxicity (Shahid et al., 2012), and may not be an immediate concern as Pb is known to be complexed and immobilised by phosphates and (hydr)oxides in soils (Zeng et al., 2017). Nonetheless, it furthers support the need for caution when applying P-fertilisers during restoration, as the introduced metals may accumulate and persist over time.

5. Conclusions

Mineral sands mining restoration has long-lasting effects in soil physicochemical characteristics, such as increased sodicity levels and decreased porosity, especially in newly restored sites. We found surprisingly high P legacy in restored sandy soils that were three to four decades old, demonstrating how long P may persist after superphosphate application – almost five times greater Total P than in native soils – while Total N may remain low despite fertilisation.

Such shifts in soil properties and stoichiometries have significant implications for microbial and plant communities developing in these sites (e.g. Kerfahi et al 2022), which are expected to be more detrimental towards native kwongan vegetation, particularly low-P adapted and P-sensitive species. As shown here, N:P ratios and carbon stocks can remain very low and may lead to a different ecosystem in relation to the target native vegetation. Therefore, the changes in restoration practices at Eneabba towards low P fertilisation is definitely encouraging to prevent P accumulation, however soil physical damage due to mining activity (i.e. high compaction) still needs addressing.

CRediT authorship contribution statement

Vinicius H. De Oliveira: Writing – original draft, Visualization, Formal analysis, Conceptualization. **Mark P. Dobrowolski:** Writing – review & editing, Resources, Data curation, Conceptualization. **Sarah Duddigan:** Writing – review & editing, Data curation, Conceptualization. **Mark Tibbett:** Writing – review & editing, Supervision, Conceptualization, Project Administration, Funding Acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. Mark P. Dobrowolski has the role of Principal Rehabilitation Scientist at Iluka Resources.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2025.108961.

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