Mine Closure 2026 – AB Fourie, G Boggs, J Heyes & M Tibbett (eds)

doi:10.36487/ACG_repo/2615_128

A statistical assessment of the applicability of agricultural soil targets to woodland habitat post-mining land use

Sarah Green Goldberg [a], Samantha Breslin [a,*], Peter Berghofer [b], Brendan Roddy [a], Aiden Wheeler [a], Lucy Stanton [a]

[a] *Egis Group, Australia*

[b] *BHP Mitsubishi Alliance, Australia*

Abstract

BHP Mitsubishi Alliance (BMA) has been collecting monitoring data on soil characteristics and soil chemistry, associated with the establishment of post-mining land use (PMLU) woodland habitat on rehabilitated landforms for over 30 years. Historically, BMA has had success establishing a woodland habitat PMLU using minimal or no topsoil growth media. However, traditionally, suitable growth media has been interpreted from an agricultural viewpoint (e.g. Hazelton & Murphy 2007) more relevant to a grazing PMLU.

Engeny Australia Pty Ltd statistically analysed soil monitoring data from 17 rehabilitation and 15 reference sites across multiple soil profiles. The assessment compared soil analyte results for established woodland habitat and reference sites and identified analytes that showed statistically significant differences between rehabilitation and reference sites. Data was then compared to agricultural target ranges/levels derived from well-known industry literature.

The data analysis indicated statistically significant differences between the reference and rehabilitation sites for several analytes. Less than 50% of samples from both rehabilitation and reference sites were within the agricultural target levels/range for selected analytes, including nitrate nitrogen, sodium, calcium, calcium/magnesium ratio, boron, calcium (% of cation exchange capacity [CEC]) and potassium (% of CEC). Soil data from topsoil stockpiles also showed low adherence to similar targets.

These findings indicate that suitable growth media for the establishment of a woodland habitat PMLU are not always constrained within the traditional agricultural interpretation, and support a case for increasing the viability and suitability of growth media sources for a woodland habitat PMLU for rehabilitated mine land across Queensland.

Keywords: *growth media, soils, rehabilitation, woodland habitat*

1 Introduction

BHP Mitsubishi Alliance (BMA) owns and operates several mine sites in the Bowen Basin, Queensland, Australia. These mines are licensed under the *Queensland Environmental Protection Act 1994* (Queensland Government 1994) via environmental authorities (EAs) and progressive rehabilitation and closure plan (PRCP) schedules. The EAs and PRCP schedules condition progressive and final rehabilitation so that land disturbed by mining activities is restored to a stable condition that does not cause environmental harm and can support post-mining land uses (PMLUs).

Rehabilitation of the sites is steered by the PRCPs as well as an industry-guided internal manual (the Manual) that provides additional internal guidance on methods to implement and achieve satisfactory rehabilitation (BMA 2022). The Manual (2022) lists soil analyte target ranges for surface soils for rehabilitation; however,

* Corresponding author. Email address: samantha.breslin@egis-group.com

in lieu of published woodland habitat-specific criteria, these ranges have been derived from well-known growth media literature that focuses on agricultural applications. The industry guidance used to inform the Manual target ranges is identified in Table 2. The Manual states that the target ranges should 'be used directly for rehabilitation with a PMLU of grazing and as a guide for rehabilitation with other land uses.'

Similar agricultural-based soil sufficiency levels/targets have been provided to the mining industry more broadly by regulatory agencies for non-grazing PMLUs in the absence of land use-specific soil sufficiency levels. One such example is the woodland habitat soil targets advised by the then Queensland Department of Environment, Science and Innovation (DESI) in the draft PRCP schedule proposed for Saraji mine during PRCP development (DESI 2024a). Note that targets were not published within the final schedule and are referenced in this paper as an example of regulator-proposed criteria considered during PRCP development.

The current EAs and PRCP schedules for the BMA sites include woodland habitat PMLU rehabilitation requirements. The woodland habitat PMLU aims to support native woodland characteristics and consists of more tree and woody understorey species compared to the grazing PMLU (DESI 2024b). The woodland habitat PMLU is not intended to be used for agricultural purposes. Because of this, the agricultural-based target ranges for soil characteristics specified in the Manual may not be directly relevant to this PMLU but have been applied historically as a guide in lieu of woodland habitat-specific targets.

BMA has successfully established woodland habitat rehabilitation at several mine sites using minimal (e.g. 0.1 to 0.15 m) or no topsoil (including Blackwater [owned and operated by BMA prior to 2024], Goonyella Riverside, Saraji, Peak Downs and Saraji South mines [Figure 1]), or alternative growth media such as spoil instead of topsoil. For the purpose of this paper, 'spoil' refers to overburden and interburden material. BMA has developed an extensive rehabilitation monitoring program for these sites over a more than 30-year period, including collection of soil data to establish the characteristics and chemistry of the surface soils that are supporting these woodland habitat rehabilitation areas. To assist with the analysis of this data, BMA has developed a rehabilitation and closure tool geospatial database to enable a more contemporary viewing platform and data repository.

This assessment compared a subset of soil data collected from the rehabilitation monitoring program for woodland habitat rehabilitation and reference sites, as well as soil data from existing topsoil stockpiles, against the Manual and DESI target ranges, respectively. The objective of this assessment was to assess the applicability of the Manual and DESI target ranges to woodland habitat PMLU rehabilitation and determine whether agricultural soil target ranges are appropriate indicators of growth media suitability.

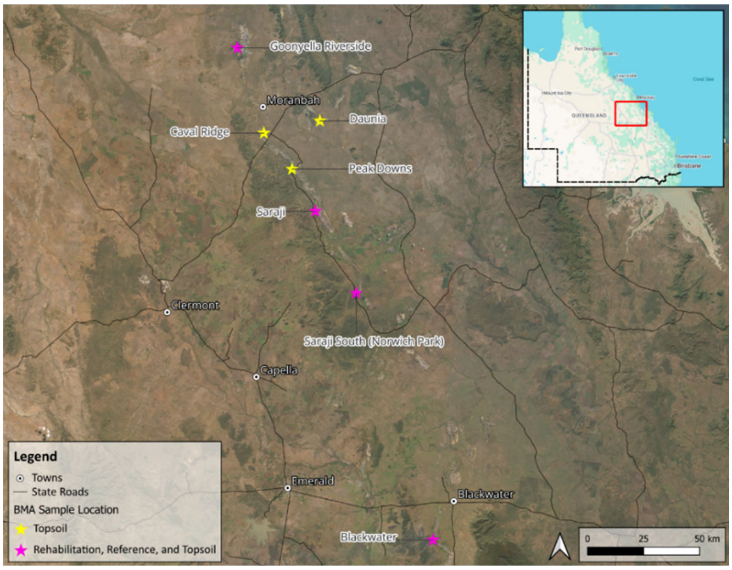

Figure 1 BHP Mitsubishi Alliance (BMA)reference, rehabilitation and topsoil sample locations for woodland habitat post-mining land use at each mine site

2 Methods

2.1 Sample datasets

Woodland habitat rehabilitation and reference site data used for the analysis included historical soil monitoring data collected from May 2018 to June 2023, totalling 128 samples from 17 rehabilitation sites and 79 samples from 15 reference sites. All rehabilitation and reference sites are located at these mines: Saraji, Saraji South (Norwich Park), Blackwater† and Goonyella Riverside.

The samples were collected across multiple site-specific monitoring programs. Because the dataset was compiled from multiple historical programs rather than a single sampling event, not all analytes were analysed for each sample. This resulted in a different number of samples for each analyte and soil profile category.

Topsoil data used for the assessment were sampled and analysed between 2017 and 2023, comprising 1,558 samples collected from topsoil stockpiles at the following mines: Saraji, Saraji South (Norwich Park), Blackwater, Goonyella Riverside, Daunia†, Peak Downs and Caval Ridge. The topsoil data is inclusive of composite samples and various profiles ranging from 0 to 4 m. A summary of the number of samples assessed in each category is provided in Table 1Error! Reference source not found..

Table 1 Number of soil samples included in the assessment for each of the categories assessed

Category	Soil profile	Number of samples per analyte
Rehabilitation sites	All soil profiles	26–128
	0 to 0.1 m	17–45
	0.1 to 0.3 m	16–38
Reference sites	All soil profiles	8–79
	0 to 0.1 m	8–27
	0.1 to 0.3 m	4–11
Topsoil samples	Composite samples and profiles ranging from 0 to 4 m	241–1,558

2.2 Soil target ranges

The Manual and draft DESI target ranges used for comparison in this assessment are summarised in Table 2.

† Blackwater and Daunia mines are no longer owned or operated by BMA but were owned by BMA during the time of the data compilation and therefore are the owners of the soil data collected during this period.

Table 2 Recommended sufficiency levels for surface soils (adapted from the Manual [BMA 2022] and DESI 2024a)

Analyte	Units	DESI (2024a) Proposed Woodland habitat target range	Manual (2022) target range	Manual (2022) comments
pH (1:5 water)	pH units	6.0–8.5	6.0–8.0	Moderately acid to moderate alkaline (Hazelton & Murphy 2007), but 6.0–6.5 is the optimum soil pH
pH (1:5 $CaCl_2$)	pH units	–	5.0–8.0	pH 1:5 $CaCl_2$ is typically 0.5–1.0 of a pH unit lower than pH 1:5 water
Electrical conductivity (EC) (1:5 water)	dS/m	< 1.5	< 0.9	Baker & Eldershaw (1993)
EC (saturated extract)	dS/m	–	< 4	Based on EC 1:5 water and soil texture, Hazelton & Murphy 2007
Chloride	mg/kg	–	< 300	–
Nitrate nitrogen	mg/kg	> 5	> 10	–
Calcium	cmol/kg[‡]	–	5–10	Hazelton & Murphy 2007
Calcium	% of CEC	–	65–80	–
Potassium	cmol/kg[‡]	–	0.3–0.7	Hazelton & Murphy 2007
Potassium	% of CEC	–	1–5	–
Magnesium	cmol/kg[‡]	–	1–3	Hazelton & Murphy 2007
Magnesium	% of CEC	–	10-15	–
Sodium	cmol/kg[‡]	–	0.3–0.7	Hazelton & Murphy 2007
Calcium/Magnesium Ratio	ratio	–	> 4	Hazelton & Murphy 2007
Cation exchange capacity (CEC)	cmol/kg[‡]	–	> 12	Hazelton & Murphy 2007
Sodium % of cations (ESP)	%	< 6	< 6	To be classified as non-sodic (Hazelton & Murphy 2007)
Copper	mg/kg	–	0.3–5	–
Iron	mg/kg	–	2–100	–
Manganese	mg/kg	–	2–50	–
Zinc	mg/kg	–	0.5–5	–
Boron	mg/kg	–	1–2	–
Sulphur	mg/kg	–	> 10	Hall 2008
Organic carbon	%	> 1	1–3	Hall 2008; Hazelton & Murphy 2007
Total phosphorus as P	mg/kg	≥ 50	8–> 20	–
Total nitrogen (Kjeldahl)	mg/kg	> 500	–	–
Emerson Class	–	> 3	–	–

[‡] cmol/kg refers to centimoles of charge per kilogram of soil and is used for exchangeable cations.

2.3 Data analysis

Woodland habitat rehabilitation and reference site soil sample data was consolidated and analysed based on selected categorical variables, including comparisons of all reference and rehabilitation samples from various soil profiles, samples from the 0 to 0.1 m soil depth profile, and samples from the 0.1 to 0.3 m soil depth profile. Statistical analyses of interest (including standard error, range and percentiles) were derived for each of the selected categorical variables for several soil analytes and compared to target values or ranges currently specified in the Manual (refer to Table 2) to establish the frequency of samples that align with the target ranges. The Manual target ranges were used for this comparison because they were the target ranges available at the time of the analysis and include a broader suite of analytes than the draft DESI target ranges, which were provided at a later date.

In addition to comparison to target value ranges specified in the Manual, the woodland habitat rehabilitation and reference site soil data was compared using the Mann-Whitney test to determine whether there were statistically significant differences between the rehabilitation and reference sites. Frequency plots were created to determine the distribution of the soil dataset, and it was found that most soil analytes exhibited a non-normal distribution. This outcome, in addition to unequal variance and a limited number of samples for some analytes, warranted the use of the non-parametric Mann-Whitney test as opposed to other statistical analyses that require adherence to the aforementioned assumptions. For this assessment, p values of < 0.05, < 0.01 and < 0.001 were interpreted as statistically significant at the 95%, 99% and 99.9% confidence levels, respectively.

Topsoil stockpile data was consolidated and compared to target values or ranges advised by the DESI in the draft PRCP schedule proposed for Saraji mine during PRCP schedule development (refer to Table 2**Error! Reference source not found.**) (hereafter referred to as 'the DESI target range') to establish the frequency of samples that align with the DESI target ranges. This was undertaken as a separate comparison to understand whether available topsoil stockpiles that may be used as future growth media sources would align with draft regulator-proposed target ranges that were being discussed at the time.

2.4 Assumptions and limitations

A number of assumptions and limitations applied to the assessment:

- The current status of the woodland habitat rehabilitation areas was advised by BMA, and Engeny did not review any rehabilitation reports as part of this assessment. BMA advised that all woodland habitat rehabilitation area data used to inform this assessment was on a trajectory to achieving a woodland habitat PMLU. The same assumption was made for woodland habitat reference sites based on BMA advice.
- There are a varying number of samples for reference and rehabilitation sites for each of the analytes tested. The number of samples was reduced as the dataset is separated based on soil profile. Smaller sample sizes for the 0 to 0.1 m and 0.1 to 0.3 m soil profiles reduce the power of statistical analyses conducted. In addition, the number of rehabilitation site samples is between 1 and 4 times greater than reference sites for all analytes assessed. As such, differences among the rehabilitation samples may be amplified (e.g. greater range) in comparison to the reference sites.
- For the 0.1 to 0.3 m soil profile there are no woodland habitat rehabilitation or reference site results for several of the analytes assessed (refer to Table 2), including copper, iron, manganese, zinc, boron, sulphur, organic carbon and total phosphorus as P.
- Where a value for an analyte is below the limit of detection, the limit of detection has been adopted. This is considered a conservative approach and allows for the analysis of a larger dataset rather than discounting the samples and skewing the remaining data.

- The power (i.e. increased chance of a type II error/false negative) of the Mann-Whitney test is reduced if there are a large number of samples in the dataset with the same value. This is evident for analytes where there is a high frequency of samples with values below the limit of detection (such as chloride).
- No multiple-comparison adjustment was applied to the Mann-Whitney test results. As such, the statistical significance results should be interpreted alongside the descriptive statistics and the broader rehabilitation context.

3 Results

Section 3.1 presents the frequency of woodland habitat rehabilitation and reference site soil samples that align with the target ranges specified in the Manual. Analytes for which there are statistically significant differences between the woodland habitat rehabilitation and reference site samples are presented in Section 3.2. Section 3.3 presents the frequency of topsoil samples that align with the DESI target ranges.

3.1 Comparison of woodland habitat rehabilitation and reference site soil samples to the Manual (2022) target ranges

Across the soil profile categories assessed, several analytes showed low alignment with the Manual target ranges for both rehabilitation and reference sites. Figures 2 to 4 present the percentage of samples within the Manual target ranges for all analytes assessed. Table 3 provides supporting summary statistics and Mann-Whitney p values for the analytes assessed.

3.1.1 All soil profiles

Figure 2 shows the percentage of samples for the woodland habitat rehabilitation and reference sites that are within the Manual target range for all soil profiles. Key results were as follows:

- More than 90% of both rehabilitation and reference site samples were within the Manual target range for EC (1:5 water), EC (saturated extract), iron, manganese and total phosphorus as P.
- Less than 90% of both rehabilitation and reference site samples were within the Manual target range for all other analytes, except pH (1:5 CaCl2) and chloride, where results varied between rehabilitation and reference sites.
- Notably low alignment was observed for nitrate nitrogen (< 2%), sodium (< 20%), calcium/magnesium ratio (< 2%), boron (< 12%), calcium (< 19%) and potassium [% of cation exchange capacity (CEC)] (0%) for both rehabilitation and reference site samples.
- The largest differences between rehabilitation and reference site samples within the Manual target range were observed for pH (1:5 water), pH (1:5 CaCl2), magnesium (cmol/kg), CEC and zinc.

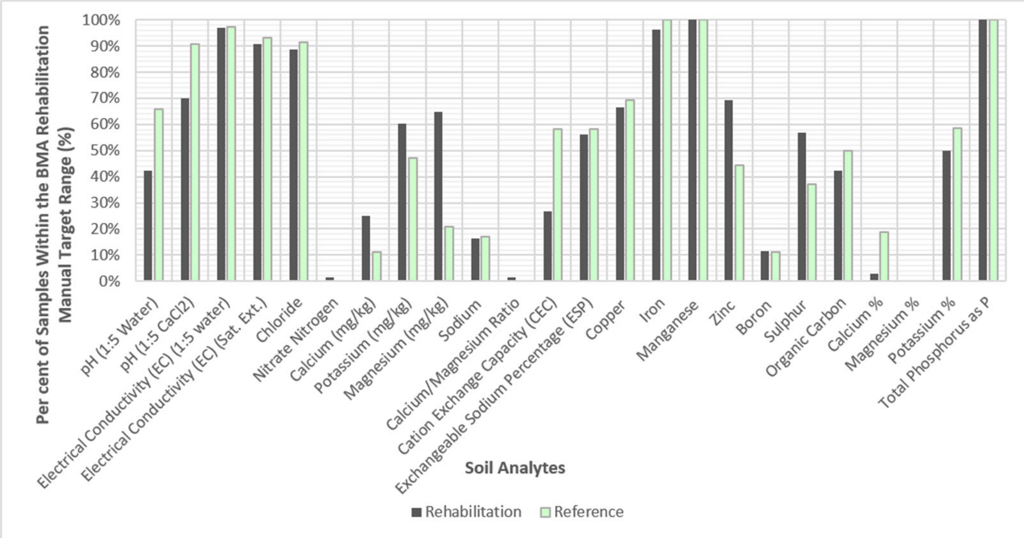

Figure 2 **Percentage of all soil profile woodland habitat reference and rehabilitation site soil samples within the Manual target ranges**

3.1.2 Soil profile 0 to 0.1 m

Figure 3 shows the percentage of woodland habitat rehabilitation and reference site samples within the Manual target ranges for the 0 to 0.1 m soil profile. Key results were as follows:

- The 0 to 0.1 m soil profile showed a similar pattern to all soil profile datasets above.
- More than 90% of both rehabilitation and reference site samples were within the Manual target range for EC (1:5 water), EC (saturated extract), chloride, iron, manganese and total phosphorus.
- Less than 90% of both rehabilitation and reference site samples were within the Manual target range for all other analytes.
- The largest differences between rehabilitation and reference site samples within the Manual target range were observed for manganese, CEC, zinc, sulphur, potassium (% of CEC) and calcium (cmol/kg).

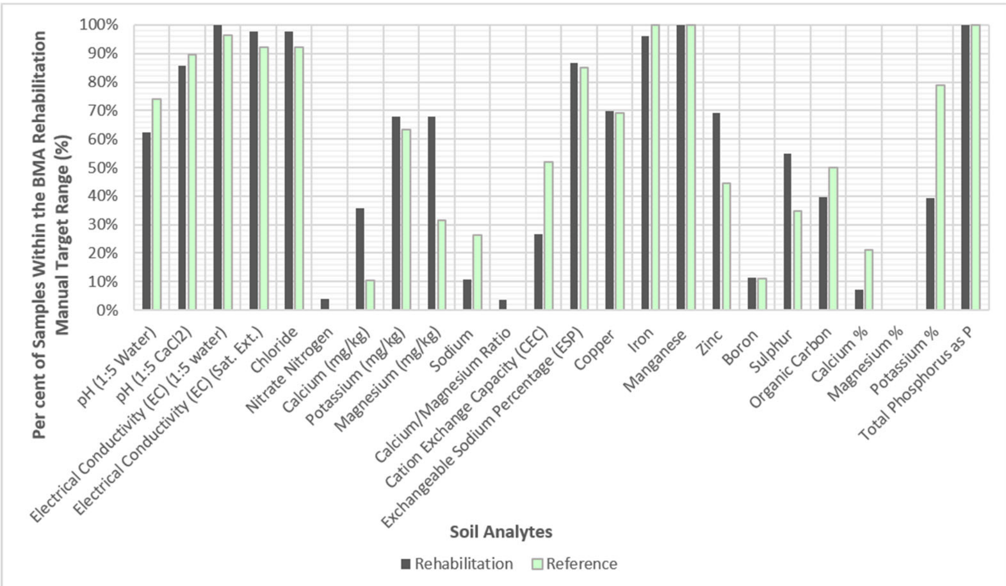

Figure 3 **Percentage of 0 to 0.1 m soil profile woodland habitat reference and rehabilitation site soil samples within the Manual target ranges**

3.1.3 Soil profile 0.1 to 0.3 m

Figure 4 shows the percentage of woodland habitat rehabilitation and reference site samples within the Manual target ranges for the 0.1 to 0.3 m soil profile. Key results were as follows:

- More than 90% of both rehabilitation and reference site samples were within the Manual target range or EC (1:5 water), EC (saturated extract) and chloride.
- Results for pH varied between rehabilitation and reference site samples. For pH (1:5 water), 90.9% of reference site samples and 34.2% of rehabilitation site samples were within the Manual target range. For pH (1:5 CaCl2), 100% of reference site samples and 72.7% of rehabilitation site samples were within the Manual target range.
- Less than 90% of both rehabilitation and reference site samples were within the Manual target range for all other analytes.
- The largest differences between rehabilitation and reference site samples within the Manual target range were observed for pH (1:5 water), pH (1:5 CaCl2), potassium (cmol/kg) and sodium (cmol/kg).

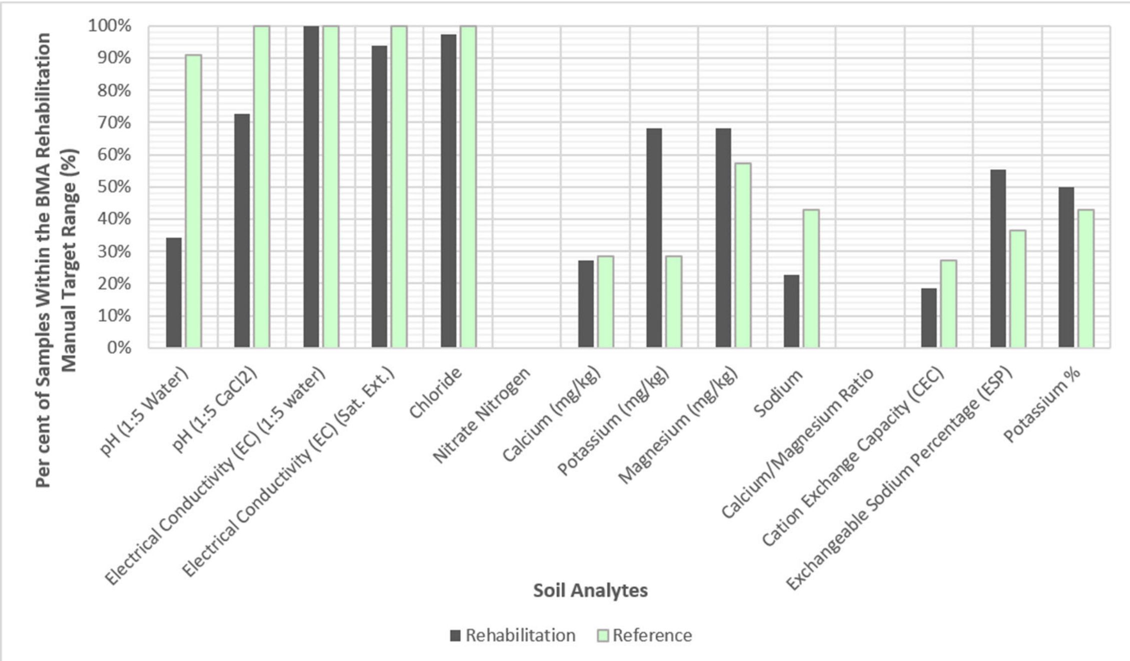

Figure 4 Percentage of 0.1 to 0.3 m soil profile woodland habitat reference and rehabilitation site soil samples within the Manual target ranges

Table 3 Consolidated summary of woodland habitat reference and rehabilitation site soil analytes compared to manual target ranges

Analyte	Unit	Target range	Soil profile	Ref n	Ref range	Ref median	Ref % within target	Rehab n	Rehab range	Rehab median	Rehab % within target	Mann-Whitney p value
pH (1:5 water)	pH units	6–8	All profiles	79	4.7–9.5	7.3	65.8%	128	4–9.9	8	42.2%	0.006**
			0–0.1 m	27	4.9–9.5	7.1	74.1%	45	4.2–9	7.4	62.2%	0.285
			0.1–0.3 m	11	6–8.7	6.8	90.9%	38	4.9–9.6	8.3	34.2%	0.001**
pH (1:5 CaCl2)	pH units	5–8	All profiles	53	5–8.3	6.4	90.6%	77	3.8–8.9	7.1	70.1%	0.196
			0–0.1 m	19	5.3–8.3	6.2	89.5%	28	4–8.1	6.8	85.7%	0.162
			0.1–0.3 m	7	5.1–6.4	5.4	100.0%	22	4.1–8.5	7.4	72.7%	< 0.001***
EC (1:5 water)	dS/m	≤ 0.9	All profiles	79	0.01–3.83	0.09	97.5%	128	0.01–2.98	0.1	96.9%	0.757
			0–0.1 m	27	0.01–0.92	0.07	96.3%	45	0.01–0.72	0.07	100.0%	0.926
			0.1–0.3 m	11	0.02–0.18	0.1	100.0%	38	0.02–0.48	0.1	100.0%	0.157
EC (saturated extract)	dS/m	≤ 4	All profiles	44	0.04–32.9	0.4	93.2%	86	0.09–25.6	0.72	90.7%	0.226
			0–0.1 m	26	0.04–7.9	0.4	92.3%	43	0.09–6.23	0.5	97.7%	0.331
			0.1–0.3 m	4	0.15–1.54	0.2	100.0%	16	0.14–4.12	0.5	93.8%	0.299
Chloride	mg/kg	≤ 300	All profiles	58	10–290	12	91.4%	122	10–2,900	20	88.5%	0.185
			0–0.1 m	26	10–290	10	92.3%	43	10–890	10	97.7%	0.154
			0.1–0.3 m	11	10–130	20	100.0%	38	10–2,900	10.5	97.4%	0.640
Nitrate nitrogen	mg/kg	≥ 10	All profiles	32	0.5–9.2	0.9	0.0%	62	0.5–10	1	1.6%	0.870
			0–0.1 m	18	0.5–9.2	1	0.0%	26	0.6–10	1.3	3.8%	0.397
			0.1–0.3 m	7	0.5–2.6	1.2	0.0%	22	0.5–3.9	0.9	0.0%	0.593
Calcium	cmol(+)/kg	5–10	All profiles	53	0.5–29	14	11.3%	68	0.1–35	3.9	25.0%	< 0.001***
			0–0.1 m	19	1.8–27	14.0	10.5%	28	0.3–21	5.2	35.7%	0.010**
			0.1–0.3 m	7	0.5–12	3.5	28.6%	22	0.1–11	3.9	27.3%	0.858

Analyte	Unit	Target range	Soil profile	Ref n	Ref range	Ref median	Ref % within target	Rehab n	Rehab range	Rehab median	Rehab % within target	Mann-Whitney p value
Potassium	cmol(+)/kg	0.3–0.7	All profiles	53	0.07–1.4	0.3	47.2%	68	0.11–1	0.4	60.3%	0.137
			0–0.1 m	19	0.14–1.4	0.4	63.2%	28	0.19–0.81	0.5	67.9%	0.580
			0.1–0.3 m	7	0.07–0.65	0.2	28.6%	22	0.13–1	0.4	68.2%	0.037*
Magnesium	cmol(+)/kg	1–5	All profiles	53	0.8–18	9.5	20.8%	68	0.5–40	3.5	64.7%	< 0.001***
			0–0.1 m	19	1.1–16	11	31.6%	28	0.5–12	3.3	67.9%	0.005**
			0.1–0.3 m	7	0.8–12	4.2	57.1%	22	0.5–8.1	3.5	68.2%	0.400
Sodium	cmol(+)/kg	0.3–0.7	All profiles	53	0.03–6.8	0.6	17.0%	68	0.02–5.4	0.2	16.2%	0.007**
			0–0.1 m	19	0.03–3.5	0.3	26.3%	28	0.02–0.56	0.1	10.7%	0.012*
			0.1–0.3 m	7	0.24–1	0.6	42.9%	22	0.02–2	0.1	22.7%	0.070
Calcium/magnesium ratio	ratio	≥ 4	All profiles	57	0.4–3.3	1.3	0.0%	75	0.1–4.4	1.2	1.3%	0.172
			0–0.1 m	20	0.8–2.9	1.5	0.0%	28	0.3–4.4	1.7	3.6%	0.975
			0.1–0.3 m	9	0.7–1.3	0.8	0.0%	26	0.2–2.2	1.3	0.0%	0.064
CEC	cmol(+)/kg	≥ 12	All profiles	72	1.6–47.5	15.5	58.3%	128	1.4–67.7	7	26.6%	< 0.001***
			0–0.1 m	27	3.1–39.3	15.6	51.9%	45	1.4–34.4	7.8	26.7%	0.017*
			0.1–0.3 m	11	1.6–25	8.9	27.3%	38	1.5–18.6	6.5	18.4%	0.286
ESP	%	≤ 6	All profiles	72	0.2–29	4.6	58.3%	128	0.1–61.2	3.2	56.3%	0.705
			0–0.1 m	27	0.2–16.3	1.3	85.2%	45	0.1–27.4	0.8	86.7%	0.091
			0.1–0.3 m	11	3.1–15	7.1	36.4%	38	0.2–61.2	3.8	55.3%	0.144
Copper	mg/kg	0.3–5	All profiles	26	0.17–17	1	69.2%	45	0.12–9	0.7	66.7%	0.337
			0–0.1 m	26	0.17–17	1	69.2%	43	0.12–8	0.7	69.8%	0.239
Iron	mg/kg	2–100	All profiles	18	11–77	29.5	100.0%	26	8.4–120	23.5	96.2%	0.667
			0–0.1 m	18	2.8–37	12.5	100.0%	26	8.4–120	23.5	96.2%	0.667
Manganese	mg/kg	2–50	All profiles	18	2.8–37	12.5	100.0%	26	3.8–20	8.6	100.0%	0.322
			0–0.1 m	18	2.8–37	12.5	100.0%	26	3.8–20	8.6	100.0%	0.322

Analyte	Unit	Target range	Soil profile	Ref n	Ref range	Ref median	Ref % within target	Rehab n	Rehab range	Rehab median	Rehab % within target	Mann-Whitney p value
Zinc	mg/kg	0.5–5	All profiles	18	0.16–4.2	0.5	44.4%	26	0.12–7	1.6	69.2%	0.031*
			0–0.1 m	18	0.16–4.2	0.5	44.4%	26	0.12–7	1.6	69.2%	0.031*
Boron	mg/kg	1–2	All profiles	18	0.2–1.4	0.6	11.1%	26	0.1–24	0.6	11.5%	0.962
			0–0.1 m	18	0.2–1.4	0.6	11.1%	26	0.1–24	0.6	11.5%	0.962
Sulphur	mg/kg	≥ 10	All profiles	27	1–70	5	37.0%	44	1–320	10	56.8%	0.051
			0–0.1 m	26	1–70	4.5	34.6%	42	1–320	10	54.8%	0.050
Organic carbon	%	1–3	All profiles	26	0.35–6	1.2	50.0%	45	0.2–6.1	1.2	42.2%	0.296
			0–0.1 m	26	0.35–6	1.2	50.0%	43	0.2–6.1	1.1	39.5%	0.347
Calcium	% of CEC	65–80	All profiles	53	20–75	54	18.9%	68	3.9–78	48.5	2.9%	0.015*
			0–0.1 m	19	23–47	36	0.0%	28	11–78	59	7.1%	0.416
			0.1–0.3 m	7	33–50	43	0.0%	22	9.2–60	49	0.0%	0.194
Potassium	% of CEC	1–5	All profiles	53	23–52	38	0.0%	68	18–64	39	0.0%	< 0.001***
			0–0.1 m	19	0.96–9.3	1.9	78.9%	28	18–49	36	0.0%	< 0.001***
			0.1–0.3 m	7	0.73–7.3	2.3	42.9%	22	2.5–8.3	5	50.0%	0.028*
Magnesium	% of CEC	10–15	All profiles	53	0.23–9.3	1.6	58.5%	68	0.48–16	4.7	50.0%	0.764
			0–0.1 m	19	23–47	36	0.0%	28	1.9–16	5.3	39.3%	0.778
			0.1–0.3 m	7	41–52	47	0.0%	22	31–55	40	0.0%	0.044*
Total phosphorus as P	mg/kg	≥ 8	All profiles	8	98–341	194	100.0%	28	75–417	224	100.0%	0.662
			0–0.1 m	8	98–341	194	100.0%	17	75–417	200	100.0%	0.954

Note: Ref = reference site samples; Rehab = rehabilitation site samples. Traffic light system: green ≥ 90%, amber 50– < 90%, red < 50%. Where p values are shown without an asterisk, the Mann-Whitney test result was not statistically significant.
*Statistically significant difference at the 95% confidence level
**Statistically significant difference at the 99% confidence level
***Statistically significant difference at the 99.9% confidence level

3.2 Statistically significant differences between woodland habitat rehabilitation and reference site soil samples

As described in Section 2.3, the Mann-Whitney test was used to identify whether there were statistically significant differences between woodland habitat rehabilitation and reference site soil samples. This section summarises the analytes with statistically significant differences for each soil profile category. The relevant p values and significance levels are presented in the consolidated results table (Table 3).

3.2.1 All soil profiles

When all soil profile results were analysed together, statistically significant differences were identified for the following analytes:

- Statistically significant differences at the 99% confidence level or greater were identified for pH (1:5 water), calcium (cmol/kg), magnesium (cmol/kg), sodium (cmol/kg), CEC and potassium (% of CEC).
- Statistically significant differences at the 95% confidence level were identified for zinc and calcium (% of CEC).
- For analytes where statistically significant differences were observed, both rehabilitation and reference site samples had less than 90% of results within the Manual target range, as shown in Figure 2 and Table 3.

3.2.2 Soil profile 0 to 0.1 m

For the 0 to 0.1 m soil profile, statistically significant differences were identified for the following analytes:

- Statistically significant differences at the 99% confidence level or greater were identified for calcium (cmol/kg), magnesium (cmol/kg) and potassium (% of CEC).
- Statistically significant differences at the 95% confidence level were identified for sodium (cmol/kg), CEC and zinc.
- For analytes where statistically significant differences were observed, both rehabilitation and reference site samples had less than 90% of results within the Manual target range, as shown in Figure 3 and Table 3.

3.2.3 Soil profile 0.1 to 0.3 m

For the 0.1 to 0.3 m soil profile, statistically significant differences were identified for the following analytes:

- Statistically significant differences at the 99% confidence level or greater were identified for pH (1:5 water) and pH (1:5 $CaCl_2$).
- Statistically significant differences at the 95% confidence level were identified for potassium (cmol/kg), magnesium (% of CEC) and potassium (% of CEC).
- Less than 90% of both rehabilitation and reference site samples were within the Manual target range for potassium (cmol/kg), magnesium (% of CEC) and potassium (% of CEC).
- Results for pH were more variable, with greater than 90% of reference site samples and less than 90% of rehabilitation site samples within the Manual target range, as shown in Figure 4 and Table 3.

3.3 Comparison of topsoil samples to the Queensland Department of Environment, Science and Innovation target ranges and sample sites

Figure 5 shows the percentage of topsoil samples that are within the DESI target range for the analytes reviewed. Reference and rehabilitation sites are also displayed for comparison. All of the topsoil samples for total phosphorus as P and 98.9% of the samples for EC (1:5 water) aligned with the DESI target ranges. For all other analytes, less than 90% of samples returned results within the DESI target range. Of the 9 analytes, 5 had less than 60% of samples within the DESI target range, including pH (1:5 water) (57.6%), nitrate nitrogen (20.4%), ESP (42.5%), organic carbon (33.4%) and total nitrogen (Kjeldahl) (53.3%).

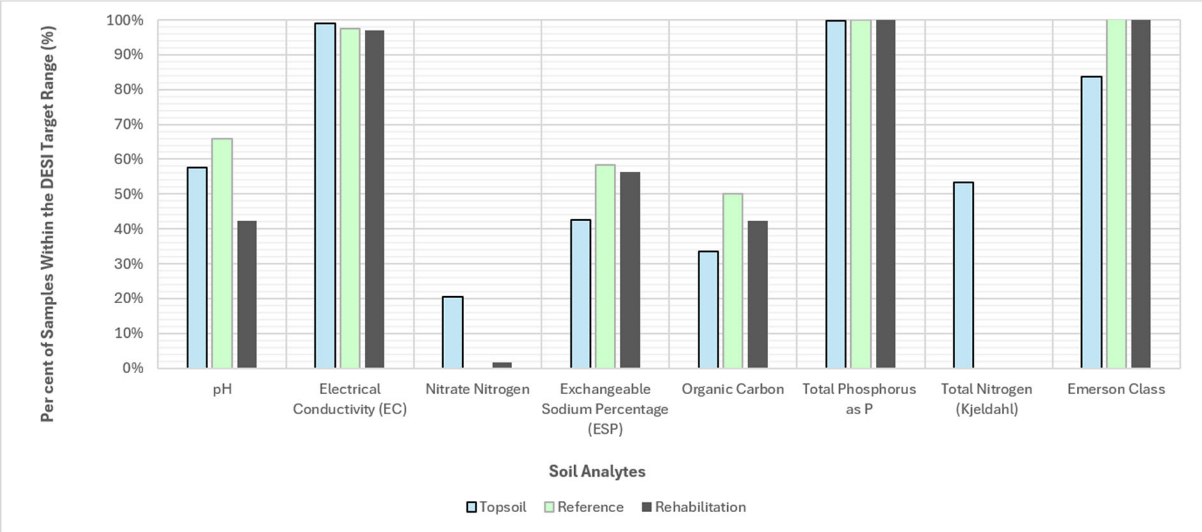

Figure 5 Percentage of topsoil samples within the Queensland Department of Environment, Science and Innovation target range

4 Discussion

Comparison of soil data collected from well-established woodland habitat rehabilitation and reference sites at BMA mine sites with the Manual target ranges indicates variable alignment with the targets, which indicates that agricultural soil targets may have limited applicability as standalone criteria for woodland PMLU. Comparison of the woodland habitat rehabilitation site data with the reference site data suggests that there are statistically significant differences between the site types for several analytes. These results indicate that dissimilarities between the rehabilitation and reference sites persist, despite both being established woodland habitats. This supports the interpretation that woodland habitat rehabilitation and reference sites can support the intended PMLU across a range of soil chemistry conditions.

The low adherence of the reference site samples to the target ranges specified in the Manual indicates that natural soil conditions for woodland habitat exist outside of the agricultural limits. The frequency of soil samples that do not achieve the soil targets specified in the Manual supports the need to avoid using agricultural-based soil target ranges as the sole criterion for woodland habitat rehabilitation. Instead, the results indicate that woodland habitat-specific soil sufficiency ranges should be informed by rehabilitation performance and relevant reference site data, particularly where established woodland habitat rehabilitation is progressing toward the intended PMLU despite soil chemistry values outside agricultural-based target ranges.

Review of topsoil data that may be used to establish future woodland habitat rehabilitation areas at BMA mine sites shows a low adherence to the DESI target ranges provided as part of a draft PRCP schedule for Saraji mine. These outcomes suggest that topsoil stockpiles managed with the intention of supporting future woodland habitat rehabilitation may be deemed unsuitable if they are compared only to agricultural standards, despite woodland habitat that is on a trajectory to support the intended PMLU having low adherence to these targets.

Overall, the results confirm that there is a variation between the woodland habitat rehabilitation and reference sites as shown in Section 3.2, and that the surface soils at both the rehabilitation and reference sites generally do not conform to the soil sufficiency levels listed in the Manual. These findings indicate that suitable growth media for the establishment of a woodland habitat PMLU is not always constrained within the range of traditional agricultural targets, and support a case for refining soil sufficiency targets for woodland habitat rehabilitation using rehabilitation and reference site data instead of relying on agricultural soil targets. There is potential in future studies to supplement the contemporary soil samples used to inform this assessment with the extensive woodland habitat soil monitoring dataset collected over more than 30 years to further assess how soil chemistry for rehabilitation sites established using minimal/no topsoil or alternative growth media changes over time and establish woodland habitat-specific soil sufficiency targets.

5 Conclusion

This statistical assessment focused on comparing soil data collected from well-established woodland habitat rehabilitation and reference sites at BHP Mitsubishi Alliance mine sites between 2018 and 2023 to an industry-guided internal manual (the Manual) target ranges to review the relevance of the targets to a woodland habitat post-mining land use (PMLU). The assessment indicates that agricultural-based soil target ranges may not always reflect the soil conditions associated with established woodland habitat rehabilitation and reference sites. Outcomes of the assessment indicate that of the 24 analytes reviewed, 18 returned results with less than 90% of samples within the Manual target range for all soil profiles assessed. The comparison also indicated that less than 50% of both rehabilitation and reference site samples were within the Manual range for nitrate nitrogen, calcium (cmol/kg), sodium, calcium magnesium ratio, boron, organic carbon and calcium [% of cation exchange capacity (CEC)]. These analyte variations were observed despite the rehabilitation monitoring data indicating that the rehabilitation is on a trajectory for supporting the intended woodland habitat PMLU.

Further comparison of the woodland habitat rehabilitation site data to the reference site data indicates there are statistically significant differences between the sites for several analytes, including pH, calcium (cmol/kg), magnesium (cmol/kg), sodium (cmol/kg), CEC and potassium (% of CEC). Dissimilarities between the rehabilitation and reference indicate that soils with significantly different chemistry can support woodland habitat PMLUs, including rehabilitation soils that are comprised of minimal or no topsoil, and alternate growth media such as spoil.

Review of topsoil stockpile soil samples that may be used to establish future woodland habitat rehabilitation areas shows a low adherence to the Queensland Department of Environment, Science and Innovation (DESI) target ranges provided as part of a draft progressive rehabilitation and closure plan schedule for Saraji mine. The topsoil stockpile comparison also indicates low adherence to the draft DESI target ranges for several analytes. This outcome suggests that topsoil stockpiles managed with the intention of supporting future woodland habitat rehabilitation may be deemed unsuitable if compared only to agricultural standards, despite woodland habitat that is on a trajectory to support the intended PMLU having low adherence to these targets.

The variable alignment with the Manual target ranges indicates that suitable growth media for the establishment of a woodland habitat PMLU is not always constrained within the range of traditional agricultural targets. There is potential in future studies to supplement the contemporary soil samples used to inform this assessment with the extensive woodland habitat soil monitoring dataset collected over more than 30 years to further assess how soil chemistry for rehabilitation sites established using minimal/no topsoil or alternative growth media changes over time and establish woodland habitat-specific soil sufficiency targets.

References

Baker, D & Eldershaw, V 1993, *Interpreting Soil Analysis for Agricultural Land Use in Queensland*, Queensland Department of Primary Industries, Brisbane.

BMA 2022, *Industry Guided Rehabilitation Manual*, BHP Mitsubishi Alliance.

Department of Environment, Science and Innovation 2024a, *Draft PRCP Schedule Proposed for Saraji Mine During PRCP Development*, unpublished draft, Queensland Government, Brisbane.

Department of Environment, Science and Innovation 2024b, *PRCP schedule P_PRCP_100779213_V1*, Queensland Government, Brisbane

Hall, R 2008, *Soil Essentials – Managing Your Farm's Primary Asset*, CSIRO Publishing, Melbourne.

Hazelton, P & Murphy, B 2007, *Interpreting Soil Test Results*, CSIRO Publishing, Melbourne.

Queensland Government 1994, *Environmental Protection Act 1994*, Australia.