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Eco-engineered soil–plant systems of nature-based design for rehabilitation of native woodlands on mined landscapes

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Abstract

Establishing self-sustaining native Eucalyptus woodlands remains a major challenge for mine closure in semi-arid regions such as Central Queensland, Australia. Long-term rehabilitation success depends on creating soil systems and landforms that are structurally diverse and functionally resilient, supporting ecological succession and heterogeneous vegetation patterns under highly variable rainfall. However, current rehabilitation practice is largely based on linear reclamation models, agricultural soil concepts and engineering approaches that emphasise uniformity and operational efficiency, often at the expense of ecological function.

This paper presents an ecologically driven, top-down framework for rehabilitating novel native woodland ecosystems. The framework seeks to recreate key structural and functional attributes of natural systems, enabling self-directed development towards resilient, quasi-equilibrated ecosystems. Ecological succession is explicitly incorporated, including shifts in soil microbial communities and transitions in vegetation from early pioneer understorey species to mature woodland assemblages with canopy, mid-storey and understorey layers. Central to the framework is the design of self-developing soils and landforms that support staged transitions from mixed exotic–native vegetation to multilayered native woodlands across heterogeneous landscapes. This requires ecological engineering approaches that align site construction with natural ecosystem processes.

Chronic topsoil shortages at mine sites further highlight the need for ecological engineering. Mine wastes and spoils can be transformed into functional earth materials, including stable sublayers and engineered soil systems. By integrating pedological principles into engineering design, these materials can form Technosols capable of evolving into self-sustaining soil–landscape systems. Combined with rock materials, they can be used to construct landforms that mimic natural colluvial landscapes, incorporating spatial variability and preferential flow pathways that enhance woodland persistence under water-limited conditions.

Evaluating novel ecosystem performance requires moving beyond simple erosion models and direct comparisons with mature reference ecosystems. Instead, assessment should focus on catchment-scale ecosystem processes, including hydrological, biogeochemical and soil–plant interactions, that indicate self-driven development and progressive improvement in ecosystem function over time

Keywords: *novel soil system, Eucalyptus woodlands, mined land rehabilitation, soil–plant–microbe interactions, ecosystem resilience*

1 Introduction

Decades of industry experience show that mined land rehabilitation has largely been designed using conventional civil and environmental engineering approaches developed for landfills, waste rock dumps and tailings facilities. These approaches emphasise risk containment (such as geotechnical stability and pollutant

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control) through uniform landforms and soil profiles, often constructed using imported materials or engineered barriers. Implementation is typically driven by fixed construction schedules, with limited capacity to respond to ecological feedback of nature's forces. Although broad geotechnical stability is critical, these approaches have design deficiencies for establishing sustainable ecosystems. Rehabilitation risks are commonly assessed using uniform landforms rather than considering the integrated behaviour of heterogeneous landform assemblages. At the ecosystem scale, rehabilitation domains such as spoil dumps, tailings storage facilities and waste rock dumps are often designed and evaluated in isolation, lacking an overarching framework that accounts for cross-domain interactions. Failure to acknowledge these in decision-making has caused many site-based rehabilitation projects to require long-term maintenance and management obligations, thus becoming a long-term environmental and financial liability. Fortunately, the mining industry has now recognised the need to shift from a risk-management paradigm towards one focused on long-term ecological sustainability and resilience, leading to final and responsible relinquishment.

Post-mining landscapes lack the geological, mineralogical and soil foundations that support natural below-ground processes and associated above-ground vegetation. Rehabilitation therefore involves the deliberate construction of novel ecosystems (i.e. not natural, but with the capacity and potential to develop into neo-natural ecosystems with sustainable functions and services) that must express the key structural and functional attributes of assemblages of habitats derived from one or more regional native ecosystems. Although these systems do not exactly replicate pre-mining conditions, they are expected to achieve comparable levels of ecological function and services in a sustainable and resilient manner that is not significantly different from natural ones in the region. The term 'novel ecosystem' used here refers particularly to newly constructed ecosystem structures in which soil system and regolith profile bear key soil biogeochemistry and hydrological attributes compatible with slow-growing native plant species typical of natural native ecosystems (such as *Eucalyptus* woodlands), excluding those supporting mainly exotic plant species and communities.

Achieving this outcome requires a clear design blueprint that defines ecosystem-scale processes, landscape roles, and domain-specific hydrological and ecological functions within the defined landscape to be rehabilitated. Understanding the hydrological roles of different landscape domains (and landforms therein) and the requirements of keystone species assemblages linked with natural soil and landforms provides a basis for specifying the structural and functional requirements of novel soil systems and landforms, as well as their spatial distribution and interactions. Rehabilitation design should therefore focus on creating adaptive, self-developing soil system–landform assemblages capable of supporting sustainable plant species assemblages and the overall communities across spatial scales.

Chronic shortages of topsoil and degradation of stored soil stripped from mining operations at mine sites further necessitate the eco-engineering of soil systems and landforms that replicate key physical, chemical and biological functions, including microbial development, nutrient cycling and water regulation. Vegetation established on these engineered substrates and landforms should express ecological traits characteristic of regional native ecosystems, such as those found in colluvial landscapes, which are typically infertile, sodic and low in organic matter, with slow nutrient cycling. Plant communities should then be able to develop along ecologically plausible trajectories exhibiting natural trends and sustainability.

Open woodlands dominated by *Eucalyptus* and *Acacia* are a defining feature of the Australian landscape and a common rehabilitation target. These systems are characterised by sparse canopies and structurally important understoreys of shrubs, grasses and herbs. At many mine sites, limited water availability and slow soil development constrain long-term vegetation sustainability. Both factors are strongly influenced by the structure and function of novel soil systems and landforms, particularly their ability to retain water at depth, resist erosion, and support understorey productivity that contributes organic inputs and soil development. In addition, significant capital inputs of organic matter is a common requirement in eco-engineering novel soil systems from spoils and mine wastes, which can be largely aided by establishing a pioneer understorey plant community in the early phase.

This paper presents a conceptual framework defining and linking nature-based ecosystem processes and functions to design requirements of novel soil systems and landforms in terms of structural and functional diversity and redundancy in spatial distribution, using woodland rehabilitation at coal mines as an illustrative case. The framework emphasises the identification of key ecosystem structures and processes characteristic of key habitats that are representative of regional native ecosystems that would be suitable for a novel ecosystem at the mined landscape. From this basis, ecosystem-scale hydrological roles as a whole and at specific domains under site-specific climatic conditions are identified. According to the defined habitat characteristics, novel soil systems and landforms that provide structural and functional diversity and redundancy to sustain target plant species assemblages derived from native habitats are designed. By applying nature-based ecological engineering, spatially heterogeneous, self-organising soil–landform systems are created. The transformation of mine wastes and spoils into functional soil systems is highlighted as a cost-effective and sustainable strategy for overcoming soil shortages and supporting long-term rehabilitation outcomes.

2 Defining novel ecosystem-bearing key attributes in a native ecosystem

2.1 Defining landscape functions and key ecosystem processes

The design of a novel native ecosystem begins with defining its overarching landscape functions, particularly its role in providing hydrological services such as water retention, subsurface storage and surface conveyance of seasonal flows. In semi-arid regions of Australia, where many mine sites are located, hydrological function is the primary system attribute underpinning landform stability and the sustainability, structure and diversity of plant communities. Within this broad landscape context, individual domains and subdomains of a novel ecosystem can be assigned specific subsidiary functions, based on their role in water and solute retention, transfer or redistribution. Recognising hydrological and biogeochemical connectivity among domains is therefore essential when designing integrated post-mining landscapes.

From this framework, the structural and functional characteristics of representative landforms that collectively deliver the defined landscape roles can be identified, including their capacity, configuration and spatial arrangement. These characteristics form the basis for designing coherent assemblages of soil systems and landforms within and across landscape domains. Landforms comprise layered soil profiles constructed from different combinations of coarse and fine materials, shaped by geomorphic processes and vegetation development, particularly within colluvial systems. Profile structure and topsoil properties jointly regulate water and nutrient storage–supply-recycling, thereby controlling the establishment, growth and long-term development of understorey vegetation and canopy tree species.

In the colluvial landscapes of Central Queensland, these hydrological services arise from the spatial integration of deep infiltration and storage of rainwater, with the short-distance surface transport of water and solutes. This integration is closely associated with the heterogeneous and repetitive distribution patterns of soil systems composed of different textures and thickness, and landform profiles of variable hydraulic conductivity and water retention capacity, characterised by varying proportions of rock, stone, gravel, sand, silt and clay (see Figures 1 and 2). Coarse, rocky or gravel-rich profiles at depth favour the establishment and persistence of deep-rooted native tree species, while more finely textured substrates support the distribution and productivity of native understorey grasses and shrubs.

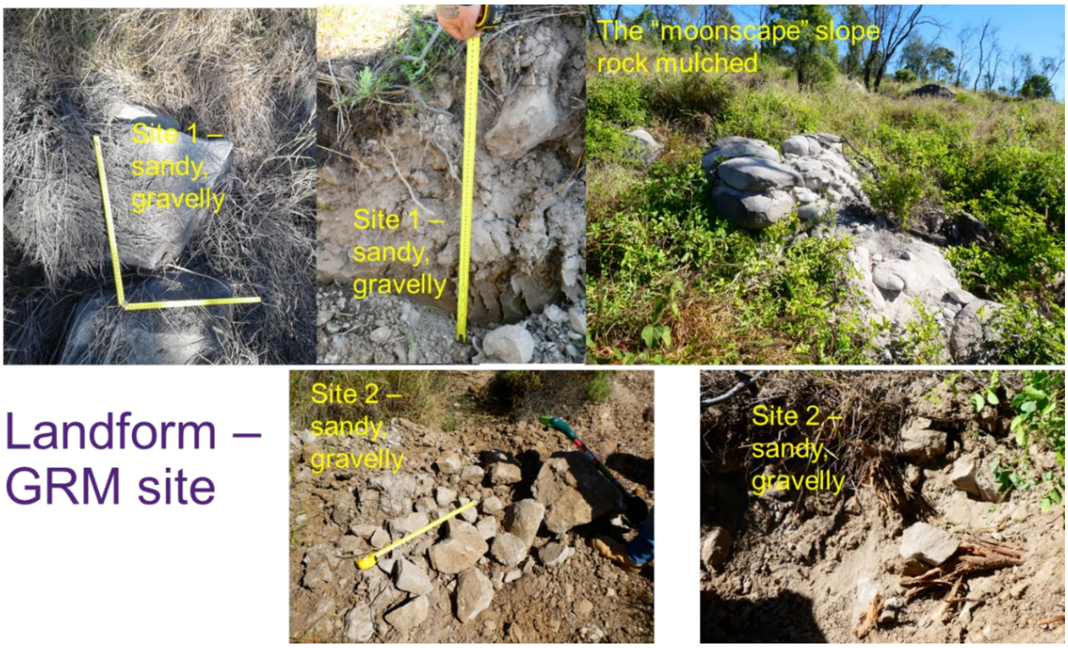

Figure 1 **Goonyella Riverside mine (GRM) field sites sampled: Site 1 (Bucket Wheel Moonscape trial slope) (pits 1 and 2 – mid-slope). Rocky slope landform, rock mulched, with extruding large boulders at the lower slope and rock fragments admixed in the surface layer (0–30 cm). Vegetation is open woodland with *Eucalyptus* species, shrubs and grasses (e.g. Rhodes; Huang et al. 2023)**

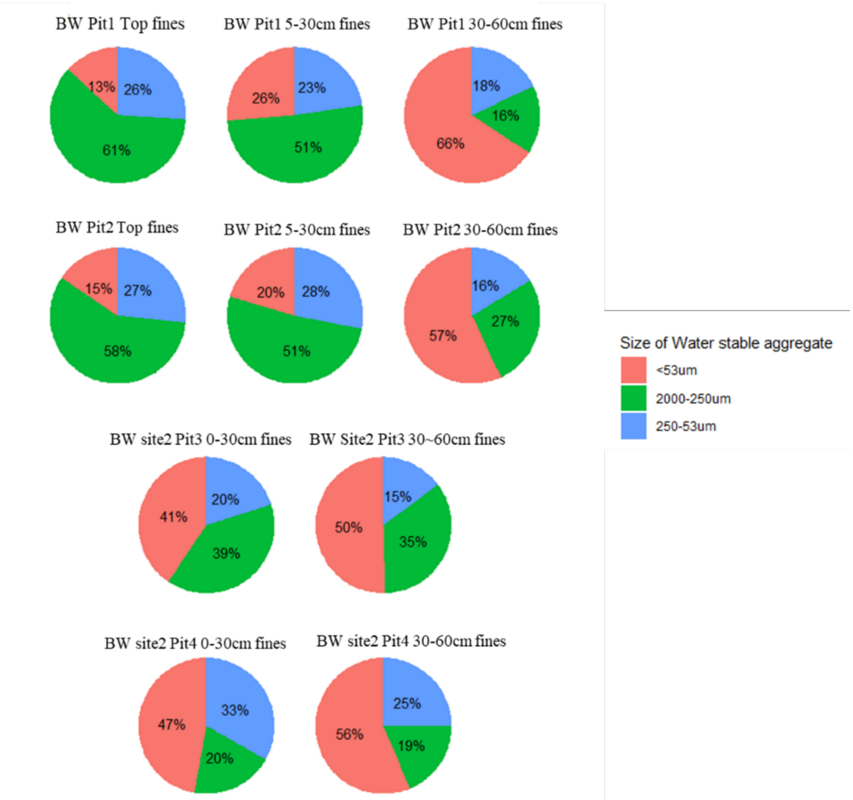

Figure 2 **Particle size distribution in soil samples from Goonyella Riverside mine Bucket Wheel (BW) site rehabilitation sites: illustrating a higher proportion of clay (< 53 µm particles) in the lower depths (below 30 cm) and a higher proportion of coarse particles (2,000–250 µm) at the surface. Site 2 samples had much higher proportions of fine and very fine particles (> 40%) in the surface layer than Site 1 (13–26%).**

2.2 Understanding key attributes of soils in native woodland ecosystem

After defining structural and functional characteristics required in novel landforms and the whole novel ecosystem, rehabilitation design should focus on ecologically linked soil–plant systems at the unit or subdomain scale. This requires identifying key soil functions (e.g. physical and chemical conditions, microbial activity and nutrient cycling) and key landform functions (e.g. profile texture, water movement and storage, and rooting depth). These factors are closely linked to the sustainability of plant systems composed of assemblages of native species.

In Queensland, soils supporting native woodlands are typically alkaline, saline and sodic. Dominant tree species in these systems include *Eucalyptus populnea*, *E. melanophloia*, *E. cambageana* and *Acacia harpophylla*, with common shrubs such as *A. salicina*, *Atalaya hemiglauca*, *Eremophila mitchellii* and the groundcover shrub *Enchylaena tomentosa* (Department of Environment and Science 2019) (Table 1). Woodland ground layers are predominantly composed of native grass species. Among the dominant trees, *A. harpophylla*, *E. populnea*, and *E. cambageana* are most associated with strongly alkaline topsoils (Erskine & Fletcher 2013). *E. melanophloia* occurs in the most saline topsoil of the native sites. *E. populnea* and *A. harpophylla* dominate the most sodic topsoil soil of native woodlands. Most plant species in woodlands exhibit a broad tolerance of unfavourable soil properties (Table 1), such as alkaline pH, elevated salinity and strong sodicity. Of the species reported, 60% were associated with alkaline soils (i.e. pH > 8.0), 83% saline soils [electrical conductivity (EC) > 200 µS/cm] and 93% sodic soil (exchangeable sodium percentage [ESP] > 6%).

Table 1 Primary physical, chemical and fertility properties of parent and substrate of native woodlands of the Brigalow Belt (Huang et al. 2023)

		pH		**EC (µS/cm)**		**ESP %**		**CEC (meq)**		**Cl (mg/kg)**	
Location		min	max	min	max	min	max	min	max	min	max
Bowen Basin	Blackwater mine	4.2		38		1		3		5	
	Norwich Park mine	8.4	9	642	1,107	8	22	30	53	360	940
	Saraji mine	6.2	7.7	737	829	–	–	–	–	–	–
	Newlands mine	6.2	9.5	269	1,163	–	–	–	–	–	–
	Mackenzie River	8.7		860		–	–	–	–	–	–
Broader Central Qld	Taunton	8.6		532		–	–	–	–	–	–
		Total N (mg/kg)		**Total P (mg/kg)**		**Extractable P (mg/kg)**		**Total C%**		**OC%**	
Location		min	max	min	max	min	max	min	max	min	max
Bowen Basin	Blackwater mine	200		130		< 1		51		0.07	
	Norwich Park mine	100	200	110	460	< 1	3	44	65	0.2	0.26

Note: – = not available. Nin = minimum, max = maximum; EC = Electrical conductivity (unit for salinity); ESP% = Exchangeable Sodium Percentage; CEC = Cation Exchange Capacity; Cl = Chloride (water soluble); N = Nitrogen; P = Phosphorus; C = carbon; OC = Organic Carbon.

Landform and soil characteristics largely determine plant community productivity and composition across spatial distance. In particular, soil water and nutrient processes should be closely aligned with the ecophysiological requirements of keystone native species and functional complementarity among understorey and canopy tree species. The physical texture of native woodland soil was found to be mostly clay soils, with loamy sand, sandy clay loam, sandy clay, clay loam and clay. However, the sublayer texture profile in these sites – such as the relative volumes of coarse materials (e.g. rocks, stones, gravels), which dictates the distribution and density of preferential flow and water infiltration into the depth of soil horizons, and the associated rooting depth of target tree species – remains unknown. Nutrient properties in soils were variable. Total N (TN) is low in the surface soil of native woodlands, with minimum TN values of 300 mg/kg and variable maximum TN values, highlighting the importance of biological N fixation by free-living N-fixing microbes and leguminous symbiotic N fixation from the atmosphere. Soil in native woodlands had very low Total P levels, ranging from < 1–1,070 mg/kg (extractable P levels ranging from < 1–76 mg/kg). Soil organic carbon (OC) ranged from 0.354.6% in the surface soil, and from 0.04–1.3% in subsurface soil, at native sites.

These key soil properties provided the basis for ecological engineering of moderately alkaline and saline mine wastes and spoils into soil systems later. It is emphasised here that low rate and persistent N and P flux would be important in native woodland soil, rather than the intensive N and P fertiliser supply as expected in fertile soils for crop and pasture production. In this regard, N-rich composts are not compatible with woodland community species, which encourages the colonisation of invasive weeds. An initial and once-off capital input of P fertiliser is recommended since most of the P is fixed by soil minerals with long-lasting P bioavailability for native plant species.

2.3 Plant species stratum typical of native woodlands and importance of understorey plants

Within Australia's Major Vegetation Groups, woodlands are primarily classified as *Acacia* woodlands, *Eucalypt* woodlands, or *Casuarina* woodlands (Department of the Environment and Water Resources 2007). Queensland's Broad Vegetation Groups further recognise open woodland communities outside the Brigalow Belt bioregion that include additional framework tree species (Neldner et al. 2019). *Eucalypt* and *Acacia* open woodlands dominate dry inland plains, including colluvial and alluvial landscapes, and gently undulating inland areas (Queensland Herbarium 2021). *Eucalyptus* woodlands are most prevalent in comparatively mesic coastal areas, while *Acacia* woodlands increasingly replace *Eucalyptus* communities with rising aridity (Johnson & Burrows 1994).

Woodland community structure varies with resource availability, particularly water and nutrients. Where canopy cover declines below threshold levels, these communities grade into open woodlands (Queensland Herbarium 2021; Burgess 2003). Open woodlands typically have much lower tree densities than woodlands or forest communities, although many framework tree species overlap between woodland and open woodland communities (Department of the Environment and Water Resources 2007). Structurally, open woodlands are characterised by trees 10–30 m tall with sparse canopy cover (< 10% cover and > 1 crown separation; Neldner et al. 2020). In these systems, the understorey represents a defining feature of community structure and function (Department of the Environment and Water Resources 2007).

The understorey comprises shrubs, grasses, herbs, small trees and cryptogams occupying vegetation layers beneath the canopy. Species diversity in the understorey is typically much greater than in the canopy, which may be dominated by only one or a few tree species (Queensland Herbarium 2021). Most floristic variation within open woodland communities is expressed within the understorey, reflecting differences in climatic zones, edaphic conditions and disturbance regimes such as grazing (Queensland Herbarium 2021). For example, *Aristida* species commonly dominate grass layers in *E. populnea* open woodlands subjected to heavy grazing pressure in Queensland (Beeston et al. 1980).

Woodlands of Central Queensland generally comprise 3 primary strata: trees (canopy), shrubs and grasses. Canopy species include structurally important framework trees such as *Eucalypts*, *A. harpophylla* and *Casuarina cristata* (Beeston et al. 1980), which define the upper stratum (Department of the Environment and Water Resources 2007; Neldner et al. 2020). *Eucalypts* are the dominant framework trees across many woodland and open woodland regional ecosystems in the Brigalow Belt bioregion (Department of Environment and Science 2019). *A. harpophylla* and *C. cristata* also function as dominant species within *Acacia* and *Casuarina* woodlands recognised in national vegetation classifications (Department of the Environment and Water Resources 2007).

In low-rainfall and colluvial landscapes such as Central Queensland, frequent canopy gaps allow for productive growth of diverse understorey communities, particularly grasses. These understorey layers play a critical role in ecosystem functioning by driving soil organic matter formation and biogeochemical processes, including biological nitrogen fixation, organic matter accumulation and nutrient cycling. Common shrub species in these woodlands include *A. salicina*, *Alectryon diversifolius*, *A. hemiglauca*, *Bauhinia carronii*, *Carissa ovata*, *Cassia brewsteri*, *E. mitchellii*, *Flindersia dissosperma*, *Geijera parviflora*, *Grewia latifolia*, *Santalum lanceolatum*, and *Terminalia oblongata*. Native grasses traditionally dominate most sites, particularly under low grazing pressure, with common species including *Dichanthium sericeum*, *Heteropogon contortus*, and *Themeda triandra*, along with species of *Aristida*, *Bothriochloa*, *Eragrostis* and *Panicum* (Department of the Environment and Water Resources 2007).

Identification and sourcing of appropriate understorey species are critical to the ecological engineering of novel soil systems and landforms, as well as novel native woodland ecosystems as a whole. Tolerant understorey plants act as key drivers during the early stages of soil system development and landform stabilisation by promoting organic matter accumulation, microbial community development and soil structural formation (e.g. formation of water-stable aggregates). Native grasses with reliable germination, rapid establishment and high biomass productivity are particularly suited as pioneer plant community (equivalent to a primary plant community naturally evolved) covering and for developing eco-engineered soils and landforms. These species can be introduced to develop novel soil systems and landforms at establishment phase, followed by shrubs and trees in a stepwise restoration sequence to enhance long-term ecosystem stability and function.

2.4 Soil–plant relation setting benchmark for eco-engineering of soil systems

Knowledge of soil–plant relationships in native woodlands provides a benchmark for the eco-engineering of mine wastes, spoils and overburden materials into resilient growth media (Technosols). In particular, these relationships define broad target ranges for soil pH, salinity, EC and sodicity, which mirror those of native woodland soils. Many native woodland species, especially dominant framework trees, naturally occur on alkaline, saline and sodic soils, and can therefore be expected to tolerate the chemical conditions typical of eco-engineered substrates derived from mine spoils and overburden.

2.4.1 Tree species

Most tree species recorded at native woodland sites were associated with alkaline and moderately to strongly sodic soils.

- Dominant open woodland trees, including *E. populnea*, *A. harpophylla*, *E. melanophloia*, *E. cambageana*, and *C. cristata*, occurred on strongly alkaline soils (pH $\geq$ 9), saline soils (maximum $EC_{1:5}$ > 800 µS cm^{-1}), and sodic to strongly sodic soils (e.g. *E. melanophloia* with ESP up to 12%, and other species with ESP > 15%).
- *A. harpophylla* and *E. cambageana* were also present in soils with high chloride concentrations (up to 1,900 mg kg^{-1}), while *C. cristata* occurred in soils with moderate chloride levels (up to 903 mg kg^{-1}). In addition, *Eucalpytus. thozetiana* was documented colonising extremely saline soils (EC up to 4,000 µS cm^{-1}; chloride up to 4,967 mg kg^{-1}) with very strong sodicity (ESP up to 53%).
- *Corymbia clarksoniana* and *C. dallachiana* were also found on strongly sodic soils, with ESP values reaching 24%.

2.4.2 Shrub and groundcover species

Shrub and groundcover species in native woodlands also exhibit strong associations with alkaline, saline and sodic soil conditions:

- Approximately half of the recorded shrub species occurred on strongly alkaline soils (56% at pH > 7.5), and 87% were associated with sodic soils.

- Among shrub species, 80% occurred on moderately to strongly saline soils (maximum EC > 400 µS cm^{-1}), with 43% colonising extremely saline soils (EC > 1,600 µS cm^{-1}) and 45% occurring in soils with moderate to high chloride concentrations (> 600 mg kg^{-1}). Dominant shrub species were generally associated with alkaline conditions (maximum pH ≥ 8.7), high to extreme salinity and moderate to strong sodicity.
- *Eremophila mitchellii*, a dominant shrub species in native woodlands and known to be associated with sodic–saline soils (Department of Environment and Resource Management, 2011), occurred in strongly alkaline soils (pH up to 9.6), extremely saline soils (EC up to 3,500 µS cm^{-1}) and highly sodic soils (ESP up to 46%).
- *Enchylaena tomentosa*, a groundcover shrub characteristic of saline environments (Department of Environment and Resource Management, 2011), was recorded on extremely saline soils (EC up to 4,900 µS cm^{-1}), as well as alkaline (pH up to 8.9) and strongly sodic soils (ESP up to 43%).

2.4.3 Grass species

Two dominant native grass species in open woodlands were also associated with strongly alkaline soils (pH ≥ 8.7), with extremely high levels of salinity and sodicity (e.g., ESP ≥ 15%):

1. *Atriplex muelleri*, a species adapted to saline environments (Department of Environment and Resource Management 2011), was found on moderately saline soils (EC up to 729 µS cm^{-1}) with strong alkalinity (pH up to 8.7).
2. *Enteropogon acicularis* occurred on strongly alkaline soils (pH up to 9.5), extremely saline soils (EC 2,890–4,200 µS cm^{-1}) and strongly sodic soils (ESP 37–46%).

Overall, these findings demonstrate that framework tree species of native woodlands in Central Queensland possess strong ecophysiological tolerance to alkaline, saline and sodic conditions. Understorey shrubs and grasses show similar adaptive traits, reflecting the prevalence of these soil conditions in naturally developed open woodland ecosystems. Together, these species provide a useful starting point for the development of diverse novel native woodlands, using integrated assemblages of tolerant tree, shrub and grass species matched to eco-engineered soil systems.

3 Ecological engineering of a novel native ecosystem

3.1 Ecological engineering of diverse novel landforms for hydrological functions

The hydrological functions and stability of landforms are fundamental to the structural and functional development of novel ecosystems. Substrate materials used to construct novel soil systems and landforms, including mine spoils and overburden, are often vulnerable to erosion, surface sealing and compaction. Consequently, an ecological engineering approach must prioritise the restoration of key hydrological services needed to support target native plant communities. This typically requires the design of structurally and functionally diverse but interconnected landforms with suitable novel soil systems arranged in spatial mosaics across mine landscapes to be rehabilitated.

Novel landforms modelled on natural colluvial landscapes may be typical of colluvial flats, undulating rocky or stony surfaces and sublayer profiles, and elevated rocky mounds. Together, these landforms create spatial heterogeneity in preferential flow paths and generate variable capacities for surface run-offs, water infiltration, retention and subsurface storage, while also moderating surface run-off and the redistribution of solutes and propagules across finer-textured areas. Well-designed landforms must maximise effective water storage while minimising erosion risk, thereby enhancing the resilience and long-term sustainability of rehabilitated landscapes.

Here, a field investigation is used to illustrate these concepts through a rock-mulched soil system and slope landforms at the Bucket Wheel site (Figure 1), which has been established for more than 15 years. The long-term stability of these landforms is closely associated with the diversity of textural assemblages and their spatial and vertical distribution (Figure 2). Although the fine soil fraction alone is dispersive and highly susceptible to erosion, the application of rock mulch promotes the development of preferential flow paths and rooting depth at the mid-upper slopes, while vegetation cover enhances the overall surface stabilisation. At lower slope positions, micro-landforms composed of shallow, layered, fine-textured soils have developed, supporting enhanced water and nutrient retention and the increased biomass productivity of colonising plants. Spoil particles (< 2 mm fraction; Figure 2) are broadly sandy in texture, alkaline (pH 8.1–9.8) and sodic (Table 2). The colonisation and establishment of grasses have resulted in marked improvements in soil chemical properties.

Table 2 Summary of soil chemistry data of fine fractions (i.e. soil) of rocky site (Bucket Wheel Moonscape trial slope – Site 1) and non-rocky site (Site 2) at Goonyella Riverside mine rehabilitation trial

Location	pH 1:5	EC 1:5 (µS/cm)	CEC (cmol+/kg)	ESP (%)
Site 1 – pit 1 top fines (0–5 cm)	8.08	80	15.44	0.79
Site 1 – pit 1 5–30cm fines	9.78	160	11.18	9.27
Site 1 – pit 1 30–60cm fines	9.26	620	40.00	47.48
Site 1 – pit 2 top fines (0–5 cm)	8.99	90	11.16	2.15
Site 1 – pit 2 5–30cm fines	9.32	140	11.92	5.09
Site 1 – pit 2 30–60cm fines	9.85	680	19.03	26.54
Site 2 – pit 3 0–30cm fines	9.81	210	15.63	10.81
Site 2 – pit 3 30–60cm fines	9.94	510	16.44	20.07
Site 2 – pit 4 0–30cm fines	8.63	2,340	19.51	10.92
Site2 – pit4 30–60cm fines	8.89	1,520	17.09	8.27

Note: Electrical conductivity (EC) and pH were determined by 1:5 water extraction. Cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) were determined via the ammonium chloride method with parallel water treatment to account for soluble salts. Soil samples: Site 1 – pits 1 and 2; Site 2 – pits 3 and 4.

3.2 Ecological engineering of novel soil systems

Following the design of novel landform structures aligned with required hydrological functions, the eco-engineering of novel soil systems underpins the diversity, resilience and long-term sustainability of rehabilitated plant communities. Plant establishment and development, in turn, drive ongoing soil formation and functional improvement. At most mine sites, shortages of suitable topsoil necessitate the recycling of large volumes of mine spoils and waste materials to reconstruct land profiles and soil layers that replicate the essential structural and functional attributes of native ecosystems.

The geochemical properties of coal mine spoils and overburdens rarely pose acute toxicity risks to plants. Although these materials typically contain soil-forming minerals, they are deficient in organic matter and available nutrients, particularly nitrogen and phosphorus (N and P). Consequently, their suitability as growth media can be rapidly improved through the incorporation of coarse rock fragments, organic matter inputs (including self-mulching by pioneer grasses), and low application rates of gypsum and N–P fertilisers. These amendments enhance soil physical structure and chemical conditions, facilitating the establishment of native species (e.g. giant speargrass, *Heteropogon triticeus*, and saltbush, *Atriplex* spp.) or non-invasive naturalised pioneers (e.g. Rhodes grass, *Chloris gayana*).

Through robust root systems, rhizosphere interactions and continuous organic matter inputs, pioneer species play a critical role in alleviating alkaline conditions, promoting salt leaching, enhancing solute transport and accelerating soil organic carbon accumulation. These processes initiate and sustain early soil development in rehabilitated landscapes. As a result, eco-engineered soils (Technosols) can progressively develop towards functional growth conditions typically characterised by pH < 9.5, EC < 1,500 µS cm^{-1} and ESP < 15%. Driven by the combined action of plant roots, soil microbial communities, spoil and tailings materials, and coarse fragments such as coal rejects and rock debris, these substrates evolve into self-organising, soil-like growth media capable of supporting long-term ecosystem development.

While basic physical and chemical criteria required for native plant establishment are relatively well defined, the development of key biogeochemical properties in Technosols derived from coal spoils and tailings remains to be established from long-term field trials. Importantly, eco-engineered soils are not equivalent to inert growth media such as potting mixes; they must evolve into soil-like substrates with self-sustaining biophysical and biogeochemical processes capable of transitioning towards a neo-natural state indistinguishable from natural soils over time.

3.2.1 Spoil characteristics in coal mines

Characterisation of spoils from mines in the Bowen Basin, Central Queensland, indicates the following key properties (Table 3):

- Salinity is generally not a critical limitation (e.g. $EC_{1:5}$ < 2,000 µS cm^{-1}) and should not restrict the growth of many native or naturalised species under semi-arid conditions. However, soluble salts can concentrate in compacted colluvial zones and low-lying areas, and can form localised salt pans or saline hotspots.
- Sodicity is commonly associated with physical compaction in colluvial plains. This can be mitigated by admixing rock fines, plant mulch or litter, and coal rejects to reduce compaction, dilute salt concentrations and improve macroporosity.
- Sedimentary rocks and sandstones (useful resources for soil and landform amendments)
    - Most sedimentary rocks and overburden or mid-burden materials have alkaline pH values of 9.0–9.5, with occasional values up to pH 10. These conditions are tolerable to many pioneer species, including grasses (e.g. Rhodes grass) and shrubs (e.g. saltbush).
    - Poorly buffered alkaline materials can be ameliorated through the combined effects of organic matter additions, gypsum application and root-mediated pH modification during plant establishment.
    - Sandstone fines are often acidic (pH ~ 6), consistent with field observations of favourable seed germination and plant growth.
- Vegetated spoils typically exhibit lower pH values (< 9), indicating progressive amelioration through biotic processes.
- Coal rejects represent a valuable onsite resource for eco-engineering Technosols due to their high content of recalcitrant organic carbon, physical bulking effects and acidic pH. Field sampling at Caval Ridge mine in the Bowen Basin indicated that:
    - Unvegetated coal reject stockpiles exhibited strongly acidic conditions (pH ~4.7), making them effective pH-neutralising amendments when blended with alkaline substrates.
    - Plant-colonised coal reject mixtures had pH values of 6.0–7.5, highly suitable for plant growth.
    - Their coarse particle size and organic carbon content improve physical structure and provide physical protection for soil microbial communities.

3.2.2 Phases of eco-engineering soil systems

The eco-engineering of coal spoils and overburden into functional soil-like growth media generally proceeds through 2 major phases.

3.2.2.1 Phase 1 (the first 3–5 years): physical and chemical establishment

Phase 1 is constrained primarily by the physical compaction associated with fine-textured spoils (e.g. silty or clay-rich materials), which limits infiltration, solute movement, water storage and root penetration. These constraints inhibit rapid chemical amelioration (e.g. salt leaching, pH adjustment) and early plant establishment. In contrast, native woodland soils typically contain greater proportions of coarse fractions (sand, gravel and rock fragments) and exhibit more heterogeneous physical properties.

At the Goonyella Riverside mine (GRM) rock-mulched slope landform, the ≤ 2 mm fraction in surface soils (0–30/40 cm) contained 20–60% sand, compared with < 15–30% in the clayey or silty clay subsurface layers. Visual assessment indicated that 20–50% (v/v) of the surface layer comprised coarse rock fragments and boulders (Figure 3). Increasing coarse fractions enhances macroporosity and hydraulic conductivity, accelerating salt leaching and reducing sodicity in the root zone. Consequently, the incorporation of rock fragments is considered the most critical first amendment when transforming fine-textured spoils into functional growth media for native open woodlands. This approach is consistent with previous recommendations for rehabilitation in the Bowen Basin.

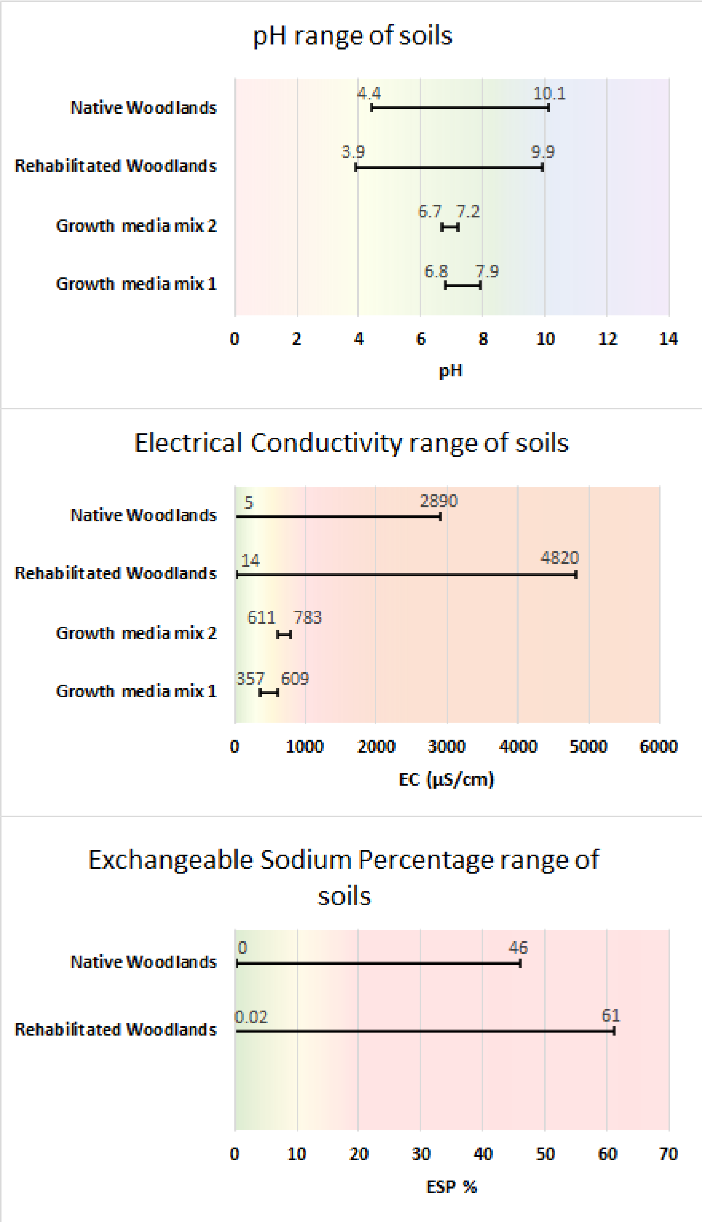

Figure 3 Comparison of pH, electrical conductivity and exchangeable sodium percentage range of soils in native woodlands, rehabilitated woodlands and growth media

3.2.2.2 Phase 2 (> 3–5 years): biological development and soil maturation

Phase 2 is driven by biological processes following the successful establishment of pioneer vegetation. Root growth, organic matter inputs and microbial activity promote the formation of organic-carbon-rich, water-stable aggregates, increased cation-exchange capacity and the development of active nutrient cycling. These processes gradually transform Technosols into structurally and functionally analogous soils to those found in native ecosystems.

Natural sodic landscapes commonly exhibit duplex soil profiles, with sandy, gravelly or rocky loam overlying dense sodic clay. A similar profile was reconstructed at the GRM trial site, where a 50–60 cm layer of rock-mulched siliceous spoil overlies a massive sodic clay horizon. This system has supported native open woodland vegetation for approximately 30 years and closely resembles natural sodic landscapes in both structure and surface vegetation composition. Accordingly, waste rock and siliceous spoils are suitable growth media, while sodic clays can effectively function as subsoil horizons in reconstructed duplex profiles.

3.2.2.3 Proof of concept

Proof-of-concept studies demonstrate the feasibility of engineering growth media from coal mine wastes. At Caval Ridge mine, both field observations and controlled pot trials showed that proportional admixtures of coal rejects, rock fines, coal tailings and organic mulch supported vigorous Rhodes grass growth. Within 14 months, initial alkaline conditions were ameliorated to near-neutral pH levels (Table 3). Similarly, field investigations at the GRM Moonscape trial slope showed that rock mulching and material blending significantly improved physical structure, hydraulic properties and rooting depth, enabling the establishment and persistence of native open woodland vegetation (Figure 2; Table 2).

Table 3 Prototyping growth media from coal mine wastes: pH and electrical conductivity (EC) (1:5 water) in coal rejects, rock fines, tailings and engineered growth media

Treatment mix (volume%)	pH (1:5 water)	EC (1:5 water) (µS/cm)
Coal rejects only	5.0–6.0	191–406
Mix 1 Coal rejects 40% Rock fines 30% Coal tailings 20% Mulch 10%	6.8–7.9	357–609
Mix 2 Coal rejects 30% Rock fines 10% Coal tailings 50% Mulch 10%	6.7–7.2	611–783
Original values before commencing treatments		
Coal rejects	4.7–4.8	1,028–1,418
Rock fines	9.0–10.0	148–397
Coal tailings	8.6–9.1	1,292–5,300

3.3 Taking plant community succession in establishing a woodland community across novel soil systems and landforms

3.3.1 Woodland species tolerance in eco-engineered soil systems

Tree, shrub and grass species characteristic of native woodlands exhibit broad tolerance to alkaline, saline and sodic soil conditions (Figure 3). These soil chemistries closely mirror those commonly encountered in rehabilitation trial sites, coal mine spoils and overburden materials. Several shrub and grass species are capable of establishing and persisting under extremely alkaline (pH > 9.5) and highly sodic conditions, making them well suited as pioneer species. Early colonisation by these plants drives rapid accumulation of self-mulching organic matter, stimulates microbial activity and accelerates the development of key soil biogeochemical processes, including nutrient cycling. Enhanced microbial and root activity promotes carbonate and bicarbonate dissolution and the progressive neutralisation or reduction of alkaline pH, as demonstrated by the proof-of-concept study (Table 3).

For long-term rehabilitation success, priority should be given to identifying productive native grass species with reliable seed yield, high seed quality and consistent germination performance. These species represent strong candidates for early colonisation of novel soil systems, providing effective surface stabilisation, biological inputs and a functional foundation for the subsequent establishment of native shrub and tree species characteristic of target woodland ecosystems.

3.3.2 Establishing a novel primary plant community using understorey species as early colonisers

Grass species exhibited tolerance to adverse soil conditions comparable to that of native tree species. Among the recorded grass species, 45% were associated with strongly alkaline soils and 63% with moderately saline soils, with all species occurring on sodic soils. Dominant grasses in native open woodlands were typically found on soils with strong alkalinity (pH > 8.7), extreme salinity and strong sodicity (ESP > 14%). Exceptions included *Megathyrsus maximus* and *Melinis repens*, which occurred at lower maximum EC values of 1,024 and 281 µS cm^{-1}, respectively. These characteristics highlight native grasses as highly effective pioneer species for colonising newly eco-engineered soil systems and landforms.

Accordingly, tolerant native or exotic annual grass species including giant speargrass (*H. triticeus*), kangaroo grass (*T. triandra*), *Acacia* shrubs and saltbush (*A. spp.*) are preferred as early colonisers of novel primary plant communities. While native species are desirable for long-term ecosystem development, non-invasive exotic crop or pasture species offer practical advantages at early rehabilitation stages, including ready seed availability, high seed quality and rapid establishment. These attributes enable fast and uniform vegetation cover across newly constructed soils and landforms; for example, using forage grasses such as silky sorghum. Establishment of pioneer species can rapidly improve the physical, chemical and microbiological properties of coal mine wastes (Table 3; Wu et al. 2019).

Shrub species in native woodlands show similarly high tolerance to adverse soil conditions. Most dominant shrubs occur on strongly alkaline soils (maximum pH.≥.8.7) and are associated with highly to extremely saline and sodic environments. Overall, 60% of recorded shrub species were linked to strongly alkaline soils and 87% to sodic soils. In addition, 68% occurred on saline soils (EC > 400.µS cm^{-1}), of which 36% colonised extremely saline conditions.

Rhodes grass is present in both native and rehabilitated woodlands and may serve as a useful indicator species due to its high tolerance of extreme soil conditions (Department of Environment and Resource Management 2011). As an early coloniser, its presence reflects early stages of soil development and functional recovery (Huang & Chen 2021). However, because it is undesirable for long-term native woodland rehabilitation, its use should be restricted to early establishment phases or experimental assessment. Where Rhodes grass is not preferred, alternative non-invasive, alkaline- and saline-tolerant annual crop or pasture species can be used as transitional pioneers to stabilise landform surfaces, enhance soil organic matter and physico-chemical properties, and promote microbial community development within eco-engineered soil systems.

3.3.3 Transition from a pioneer plant community into a woodland community

Plant community succession is explicitly embedded within the rehabilitation design framework. Developing soil systems and stabilising landforms are used to facilitate staged transitions from mixed exotic–native understorey assemblages to multistoreyed native woodland communities across heterogeneous landscapes. As novel soil systems improve in physical, chemical and biological properties (e.g. reduced pH and EC, increased soil organic matter and microbial activity), and as landforms stabilise hydrologically and structurally, different native plant assemblages are progressively introduced. These assemblages are spatially aligned with contrasting soil textures and landform types (e.g. fine-textured valley plains versus coarse-textured rocky upland slopes), reflecting the structural and functional diversity of native woodland ecosystems in the region. Such vegetation mosaics, aligned with soil variability and successional trajectories, promote progressive development of hydrological function and ecological diversity across rehabilitated mine landscapes.

Rehabilitation of target woodland communities begins with the establishment of a pioneer (novel primary) plant community to colonise, stabilise and initiate soil development across newly constructed landforms under local climatic conditions. This initial community typically comprises a limited suite of tolerant understorey species and/or exotic, naturalised, non-invasive grasses and shrubs that are already locally adapted. Grass species from native woodlands exhibit tolerance comparable to, and often exceeding, that of native tree species under alkaline, saline and sodic conditions. Among recorded grass species, 45% were associated with strongly alkaline soils and 63% with moderately saline soils, with all species occurring on sodic soils. Dominant grasses of native woodlands typically occurred on soils with strong alkalinity (pH > 8.7), extreme salinity and strong sodicity (ESP > 14%) (Figure 3).

These grasses are therefore highly effective pioneer species for establishing primary plant communities on newly eco-engineered soil systems and landforms. Through rhizosphere processes, enhanced solute transport, accumulation of self-mulching organic matter and the development of forest-soil microbial communities (including fungi), pioneer grasses play a critical role in alleviating alkaline conditions and accelerating soil formation. This early soil development creates favourable conditions for the subsequent establishment of canopy tree species (You et al. 2016; You et al. 2026).

Understorey vegetation – comprising small trees, shrubs, herbs, grasses and lichens – occupies the strata beneath the canopy and typically supports much greater species diversity than the woodland canopy itself, which may be dominated by one or a few tree species (Queensland Herbarium 2021). Woodland communities may transition to open woodland structures where and when soil nutrient availability and water supply become limiting to biomass productivity and canopy development (Burgess 2003; Queensland Herbarium 2021). Dominant woodland tree species – including *E. populnea, A. harpophylla, E. melanophloia, E. cambageana*, and *C. cristata* – have all been recorded on strongly alkaline soils (pH ≥ 9), with high to extremely high salinity (EC > 800 to > 1,600 µS cm^{-1}) and strongly sodic conditions (ESP > 15%) (Figure 4).

(1). a) an overview of rock mulched slope landscape b) rocky/gravelly soil (spoils) overlaying sodic clay (overburden)

(2). Native open woodland in Central Queensland adjacent to coal mines: gravelly surface soil

Figure 4 Visual profiling of: (1) Trial landform at Goonyella Riverside mine, with different treatments of spoils and rocks, supporting 30-year-old native open woodland (established in 1991), which is composed of (a) rocky/gravelly soil (spoils) over (b) heavy sodic clay, compared to (2) an unmined native open woodland with gravelly surface soil features (Huang et al. 2023)

3.3.4 Process-based assessment of a novel woodland community development

Novel plant communities that develop on reconstructed landforms will not necessarily replicate pre-mining native plant communities (Erskine & Fletcher 2013; Figure 4). Accordingly, it is inappropriate to apply quantitative indicators derived from mature 'reference' ecosystems directly to newly constructed or early-successional ecosystems – much like comparing adolescents with fully developed adults. Nevertheless, rehabilitation outcomes must still be evaluated in a rigorous and defensible manner. Rehabilitation success is therefore best assessed using site-specific indicators that reflect the development of hydrological function and soil biogeochemical processes, and track ecosystem trajectories towards those of native systems over an intermediate time frame. The goal is to demonstrate that the structure and function of novel soil systems and landforms are sufficiently developed to resist degradation and maintain self-repair capacity (i.e. ecological resilience).

Novel plant communities established on eco-engineered soil systems and landforms should exhibit key ecophysiological and ecological characteristics of relevant local native ecosystems rather than strict compositional identity. For example, in colluvial landscapes, these characteristics include infertile and sodic soil profiles, low organic matter and nitrogen availability, slow nutrient cycling, and the co-existence of bacterial- and fungal-dominated soil microbial communities. This can be achieved through the use of an integrated indicator matrix capturing key structural and functional attributes derived from representative habitats of target native ecosystems within the local region or catchment. Such indicators may include physical heterogeneity (both vertical and horizontal), development of biophysical soil properties (e.g. stable organic matter–mineral associations), biological nitrogen fixation and microbially mediated litter decomposition. Assessment of vegetation should focus on functional contributions across strata, recognising the complementary roles of understorey species and canopy trees in driving soil development, hydrological performance and ecosystem resilience.

4 Conclusion

This paper presents a process-based framework for rehabilitating novel native ecosystems for post-mining landscapes, using open woodland restoration as an illustrative case. It argues that conventional, uniform risk-containment approaches are insufficient for achieving long-term ecological sustainability and instead advocates for ecological engineering grounded in ecosystem processes, hydrological function and soil–plant interactions. Central to the framework is the design of spatially heterogeneous landform and soil-system assemblages that emulate the key structural and functional attributes of regional native woodlands – particularly colluvial landscapes characterised by alkaline, saline and sodic soils, low fertility and slow nutrient cycling. By leveraging the demonstrated tolerance of native woodland trees, shrubs and grasses to these conditions, mine spoils and overburdens can be transformed into self-organising Technosols and soil systems through the strategic use of coarse materials, organic inputs and pioneer vegetation.

Rehabilitation success is driven by a staged successional pathway, beginning with a pioneer plant community dominated with tolerant understorey and grass species that stabilise landforms, improve soil structure and chemistry, and initiate microbial and biogeochemical processes. As soil systems and hydrological functions develop into quasi-equilibrium states approximating natural ones, diverse native plant assemblages can be progressively established in patterns aligned with soil texture and landform position, promoting ecosystem resilience and functional diversity. Because novel ecosystems do not replicate pre-mining ecosystems exactly, the paper emphasises process-based, site-specific assessment rather than direct comparison with mature reference systems. Indicators of hydrological performance, soil biogeochemistry, physical heterogeneity and functional vegetation roles provide a robust basis for evaluating whether rehabilitated landscapes are on credible, self-sustaining ecological trajectories.

Overall, the framework demonstrates that transforming mine wastes into functional soil systems combined with nature-based landform and plant community design offers a cost-effective, scalable and resilient pathway for long-term woodland rehabilitation and closure outcomes, reducing perpetual management liabilities while restoring ecosystem function at the landscape scale.

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