

Transforming engineering into ecological engineering for developing resilient ecosystems on mined landscapes

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Abstract

The rehabilitation of mined landscapes has reached a significant crossroad. There are rising regulatory and community expectations and financial costs, but operational success has made very slow progress across the mining and minerals sectors. The history of rehabilitating mined landscapes is relatively short, with prescriptive approaches encouraged by the introduction of the US Surface Mining Control and Reclamation Act in 1977. During these four decades, the goalpost of closure standards has shifted from non-pollution in the 1980s, sustainable land use since 1990s, to 'resilient ecosystems', in response to the society's acceptance of climate change and uncertainties. In the meantime, operations at mine sites have been largely resorting to 'environmental engineering' (or briefly referred to as 'engineering') thinking and approaches to reconstruct and rehabilitate mined landscapes for economic and natural land uses. The continuation of 'engineering' from mining into rehabilitation is because this mindset is conducive to 'engineering' methods which are prescriptive and definitive in operational process, such as land contouring, topsoil sheeting, and seed sowing, fertilisation, drainage installation, and slope stabilisation. In contrast, the transition into 'ecological' thinking is much needed to design and create new ecosystems at an operational level. 'Ecological' methods are descriptive and characteristics of undefined operational requirements and associated risks in the short/intermediate term. In many cases, agroecosystems (e.g. pastures) have been adopted as post-mining land use of mined landscapes, such as coal mines in central Queensland. Agroecosystems at remote mine sites may not be sustainable due to high energy requirements to improve and maintain the productive capacity for economic outcomes in landscapes with inherently infertile soils and low rainfall. Nor are they 'resilient' due to the lack of ecological diversity and functional redundancy. In other cases, the goal is to restore the mined landscapes back to seemingly 'original' ecosystems, based on comparing short-term ecological features with non-disturbed 'reference sites', while disregarding the loss of regolith structure and landform diversity after mining.

It is time to shift the paradigms of research and operations from 'engineering' to 'ecological engineering', by integrating prescriptive engineering processes with biological and ecological dynamics for developing (rather than superimposing) resilient ecosystems. Environmental engineering at individual domains of a mined landscape is necessary for abatement and avoidance of major environmental risks (e.g. geochemical pollution, massive erosion), but natural forces take over the design and development of newly recreated systems as soon as site 'engineering' stops. 'Ecological engineering' advocates a systematic program to create a new ecosystem which includes diverse and redundant ecological processes and functions. Most importantly, 'ecological engineering' aims to harness natural forces in designing and recreating new ecosystems. The assessment of 'ecological engineering' success in developing resilient ecosystems requires the quantitative and qualitative assessment of the trajectory to develop the ability (i.e. resilience) to adapt, reorganise and redesign the recreated systems while coping with ongoing disturbances to future ecosystems driven by climate changes. Although the term 'ecological engineering' was coined in the 1970s, it has not been systematically adopted into the operations of mined landscape rehabilitation/reclamation. Meanwhile, there has been a lack of adequate long-term trials designed with ecological engineering principles. As a result,

‘ecological engineering’ knowledge and knowhow are urgently required for designing site-specific and field-operable methodology and technology, to abate the energy underpinning environmental risks and accelerate the development of resilient ecosystems, with environmental stability, and adaptive ecological processes and ecosystem services.

Keywords: *mined landscape rehabilitation, ecological engineering, new ecosystems, resilience, development trajectory*

1 Introduction

Since the enactment of the Surface Mining Control and Reclamation Act in 1977 to regulate environmental impacts of coal mining in the United States, the minerals industry has attempted to rehabilitate disturbed lands and create new ecosystems in mined landscapes. Meanwhile, government regulations and community expectations for rehabilitation and closure outcomes have shifted from the initial requirements of pollution control and revegetation to now, resilient ecosystems, which are required to stand up against extreme weather events for many centuries to come (Figure 1). However, rehabilitation methodology and operational practices on sites have so far largely relied on ‘environmental engineering’ to address mainly domain-specific environmental risks (e.g. erosion and metallic drainage pollution from tailings storage facilities [TSFs] and waste rock dumps [WRD]). An overemphasis on particular bauxite mine rehabilitation success, that follows the model of successional development called the ‘initial floristic composition’ (Koch & Ward 1994), has led current practitioners to believe that the introduction of keystone plant species representative of existing reference ecosystems, in a one-stop-shop approach, is required. This approach, when applied across other mine sites, appears to have led to practitioners ignoring some of the key drivers of soil and land processes in the development of plant communities, especially the soil-land developmental effects of pioneer plant communities. We have observed that a plant-only focused approach, based primarily on direct seeding of native species and not carefully considering regolith challenges, has resulted in frequent failures of plant establishment and thus wasted considerable quantities of precious native seed resources and time (or opportunities). Infant soil and land systems often cannot support the ecophysiological requirements of many slow-growing native plant species, except for early settlers of pioneer plant species that are tolerant of land disturbances and conditions such as altered soil chemistry and shallow rooting depths.

A very small number of successful cases do exist at shallow open cut mines (Koch 2007; van Aarde et al. 1996), with careful conservation and immediate replacement of fresh topsoil resources and minimal landform alteration. In most cases, little confidence could be assured about whether the newly created and infant ecosystems could survive in years or develop across decades without deviation from the ‘reference sites’, let alone ecosystem resilience to self-adapt to future climatic conditions. Long-term and system-integrated field trials (> 10 years) are too rare to draw conclusions between soil and land development and plant community development at mined landscapes. This style of research is urgently needed to aid mined landscape rehabilitation over the coming decades.

Current engineering processes tend to prioritise short-term risk control at specific mine domains (such as, TSF, WRD, overburden dumps, pits or voids), rather than long-term ecosystem development across the whole landscape that falls under a mineral lease. Current methods to assess rehabilitation outcomes have been largely based on superficial comparison of landform and vegetation similarities between very old ecosystems (i.e. ‘reference sites’ of natural ecosystem) and the newly created ecosystems, in addition to other criteria (e.g. safe, stable and non-polluting). However, the assessment based on the development trajectory of newly created ecosystems raises a new debate: when can we confidently handover the new ecosystems to the future managers and nature, with continuation of dynamic ecosystem processes and functions and without major environmental risks? Against the backdrop of expected completion criteria of resilient ecosystems, it is time for regulators, industry sectors and researchers to examine the trials and errors from past rehabilitation experiences in open cut mines (e.g. bauxite, coal) and mine waste landscapes (e.g. bauxite residues, sulfidic tailings and waste rocks, coal tailings). This process may help us advance our knowledge, technological capability and, more importantly, our confidence on the developmental trajectory of new

ecosystems created now, exhibiting adaptive ecosystem functions and services (i.e. resilience), but without major environmental risks into the infinite future.

The present paper aims to discuss current limitations in designing and implementing rehabilitation on isolated domains of mine sites, within the context of soil and land systems and ecosystems. It aims to highlight the importance of system analysis and integration across the whole mined landscape, by assimilating system knowledge of regolith and landforms, soil and land processes in driving plant community development, and ecosystem processes and resilience. The discussion prefers to use mined landscapes, rather than 'mined land', to elevate our attention to the system scale. By integrating these system principles, we advocate the necessity to shift from 'engineering' focused to 'ecological engineering' in rehabilitation design and implementation on site. If we accept that natural forces will take over shaping the development of new ecosystems designed today, how can we change regulatory assessment approach and criteria to reflect the trajectory of soil and land systems and functional diversity that underpins the development of infant ecosystems newly created on mined landscapes, rather than the current superficial comparison (e.g. species diversity) with 'reference sites'? Finally, we point out the urgency to commence formal education and professional training for preparing current and future workforce in 'ecological engineering', through the partnerships among governments, universities and industry sectors, to ensure that this approach can be implemented.

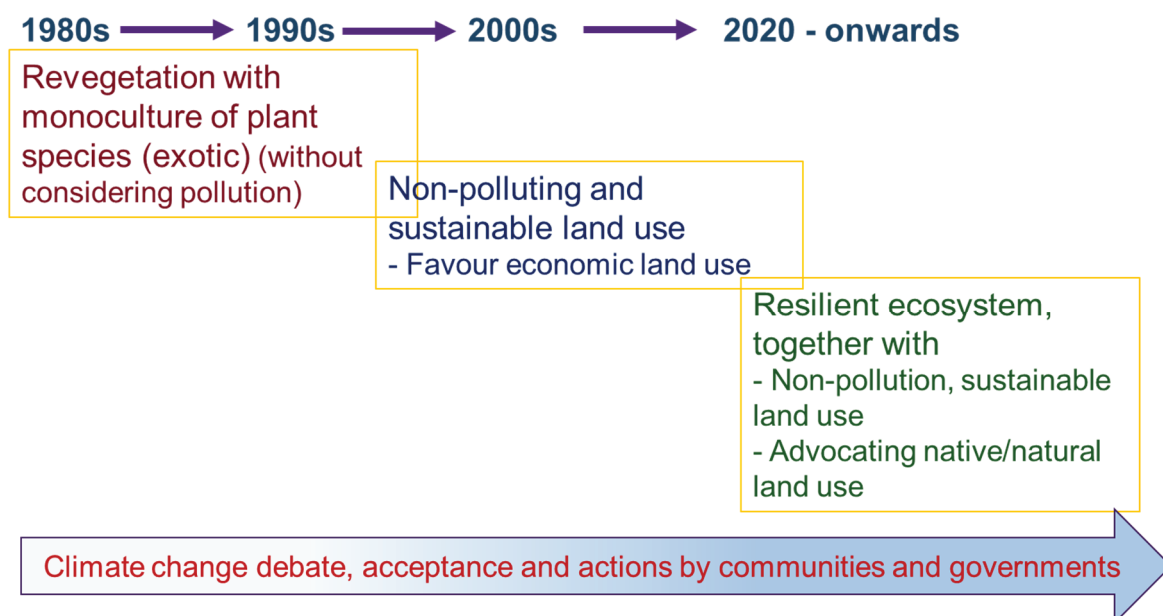


Figure 1 Overview of the shifting goal posts of regulatory standards and completion criteria for rehabilitation of mined landscapes from environmental management into resilient ecosystems

2 Current limitations of mined land rehabilitation in Australia

Society has accepted that mining is only a very short episode in the long history of land use for human benefits, and desires that it ensures the landscapes mined are rehabilitated or restored to be safe, stable, non-polluting and sustainable in structure, processes and functional services. In response to regulatory and community pressures, site-efforts have been invested to implement rehabilitation programs at many mine sites by environmental engineering projects. These projects have treated each domain as an isolated and closed system, rather than components of a total ecosystem at the landscape scale. In recent years, 'ecosystem resilience' has been added to desired completion criteria, in recognition of looming challenges of climate change.

So far, stories about successful rehabilitation meeting current regulatory goals have been hard to come by, apart from a small number of well-publicised cases, such as Alcoa bauxite mine restoration for native Jarrah forests (about 1,000 ha) (Gardner & Bell 2007) and native sand dune plant communities at North Stradbroke

sand mine (Gravina et al. 2011). These two sites have progressively moved through landscapes such that topsoils and landforms were only briefly impacted (compared to Bowen Basin coal mines, Mount Isa Cu-Pb-Zn mines), without the persistence of foreign landforms (e.g. dams). More importantly, the rehabilitation programs at these two mines have assimilated critical knowledge and practices about the role of soil ecology and native plant ecology in restoration and designed landforms and ecosystems with clear ecosystem processes and services in mind. These include conservation of fresh topsoil and associated genetic (seeds, microbes) banks, soil ecological and plant ecophysiological requirements of native plant species, and ecohydrology for local water resource supply. These have benefited from many decades (since 1960s) of research and training investments in catchment hydrology and native plant ecology, by government departments (e.g. Department of Conservation and Land Management, Kings Park Science), research institutions (e.g. CSIRO Forestry), and universities (e.g. The University of Western Australia, Murdoch University) in Western Australia.

Most mined landscapes in Australia have not been so fortunate. Some of the key limitations and associated unanswered research questions are summarised below, in the context of ecosystem resilience:

1. Fresh topsoils are not just competent physical substrates, but very rich in native seed banks and microflora and fauna, which are not easily replaceable by artificial inputs. There are significant shortages of topsoil resources across mine sites, even poor soils with the minimal properties of physical and chemical competence for plant growth. This has been attributed to inherently thin soil layers across natural landscapes (e.g. at many Fe-ore mines) and inadequate early planning to protect and conserve soil resources on site (e.g. Bowen Basin coal mines at alluvial plain). It is economically and ecologically impracticable to excavate and transport topsoil from natural landscapes in the surrounding landscape. Can abundant non-soil pedolith materials (e.g. overburdens, tailings) be developed into soil by using short-term and intensive engineering inputs to initiate and accelerate bioweathering of minerals and pedological processes to form soil? Can focused and intensive topsoil replacement be used to create new corridors and colonies for establishing genetic flow into the new ecosystem?
2. The rehabilitation design and methodology have been largely the continuation of engineering practices to address the safety and stability of homogenous landforms (e.g. straight slopes of dam walls, spoil and waste rock dumps), without adequate consideration of ecological principles: the diversity and redundancy in soil properties (particularly physical structure), micro-/macro-landforms underpinning the development of plant community and ecosystem resilience.
3. The persistence of engineered landforms (e.g. spoil slopes, dam walls) after mining inhibit the development of ecosystem processes to integrate different domains in a mined landscape, such as water and solute transport processes. Current engineering processes tend to treat each mined domain as an isolated system, without adequate understanding of domain interactions and their contribution to the whole landscape and ecosystem processes.
4. The rehabilitation design and approaches implemented across a mined landscape are not designed to include key ecosystem services and processes that need to be enabled by engineering processes at individual domains (apart from supporting plant community).
5. There has been inadequate expertise and site-capability to shift rehabilitation from 'engineering' into 'ecological engineering' in design and implementation. In coming decades, mining industry and environmental service sectors will require a continual supply of future generations of ecological engineers possessing the knowledge and experiences in both ecosystem ecology and environmental engineering.

3 An overview of system concepts: regolith, landform and ecosystem

We briefly introduce regolith, landform, and terrestrial ecosystem, in order to illustrate mining impacts on vertical and spatial scale of system structure, processes and functions and key requirements in designing and creating new ecosystems to rehabilitate the mined landscapes.

The regolith is referred to as the terrestrial zone from land surface to the weathering front of bedrock, which is organised in the order of 'saprolith' in the depth above the bedrock and 'pedolith' on top (Pope 2015; Wilford et al. 2016) (Figure 2). The in situ developed saprolith is composed of slightly weathered saprolite, the latter of which may be rich in dissolved salts and deficient in organic matter and biological activities, without macropore structure. The 'pedolith' composition and thickness is the combined result of pedogenesis through biological weathering and bio-mixing of saprolite in situ and the loss/gain of transported materials from/to offsites (Wilford et al. 2016). The pedolith is composed of biologically active soil horizons at the surface and non-soil mineral horizons (i.e. without ped structure) important to regulation of water and salt movement in depth. The mineral and organic composition and physical thickness of pedolith is the consequence of in situ geological processes (e.g. weathering) and transport processes (e.g. sedimentation in alluvial plains and valleys, and erosion in mountain slopes).

The characteristics of regolith profile and topographic features (including vegetation) shape micro- and macro-landforms in structure and functions, such as water distribution (i.e. water shedding or water-catching), and rates and amounts of material gain or loss (e.g. erosion versus deposition of soil particles, salts, and organics) (Fu et al. 2013). Micro-landforms at patch scale are closely related to soil properties and in situ vegetation types (e.g. grass, trees, close canopy, open canopy), while macro-landforms are spatial areas which are capable of significantly changing the flow and distribution of water and materials across a spatial distance, such as wetlands, plains, and slopes (Fu et al. 2013). It is emphasised that individual landforms are structurally and functionally interconnected in a natural landscape, dynamically shaping and facilitating further development of soil and land processes and plant communities. The removal/alteration of one landform element can have dramatic impacts on the flow of materials and water into/out of neighbouring landforms.

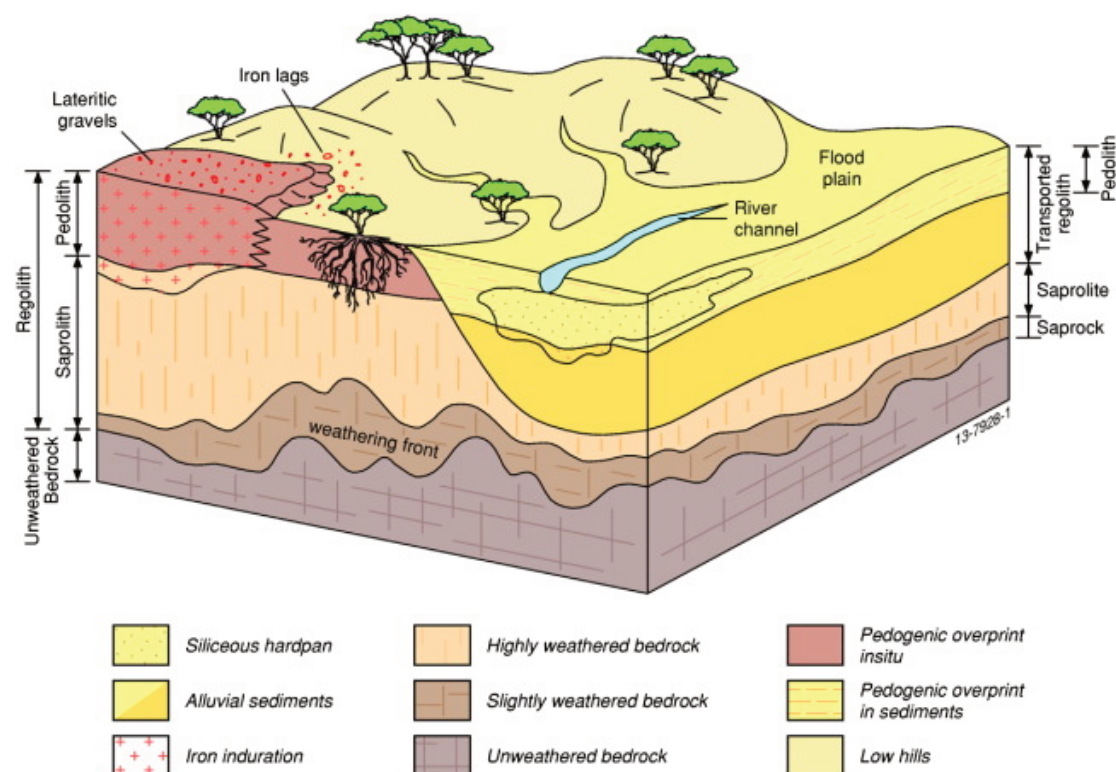


Figure 2 A conceptual diagram of regolith from Wilford et al. (2016)

We need to recognise that terrestrial ecosystems are composed of biotic and abiotic components (in both the above-ground and the below-ground), which are open systems possessing dynamic flows of energy and materials internally across different domains and externally with upstream and + landscapes and ecosystems.

At a spatial scale, a terrestrial ecosystem is composed of:

1. The vertical system of regolith of heterogenous profile make-up: including the gradient of mineral to organic phases from the weathering front of bedrocks to the soil horizon where biological activities are most active.
2. A collection of adjacent regolith across an immediate spatial area which determines the characteristics of the associated landforms and plant communities.
3. A collection of diverse landforms across a landscape of defined size enables and drives ecological processes, including the flow of materials (e.g. salts and sediments), water (e.g. surface runoff, infiltration, evapotranspiration), and biota (e.g. genetics of microbes, fauna and plants). Soil and land development drives plant community development across the time frame of years (e.g. topsoil processes) to millions of years (e.g. regional land and geological processes) (Laliberté et al. 2013; Walker & Wardle 2014).

Landscape patterns and processes drive the development of ecosystem processes and functions. In terrestrial ecosystems, it is well known that soil and land processes drive the development of species characteristics and diversity in plant communities (Laliberté et al. 2013; Walker & Wardle 2014). Regional plant communities are driven by long-term geological processes, such as major uplift and crustal movements and associated massive erosion and deposition, over millions of years (in most cases) (Walker & Wardle 2014). Soil processes, such as nutrient (especially N and P) cycling and supply drive the inverse relationship between the productivity and species diversity in plant communities at scales from micro-landforms to landscapes, with species rich and productivity poor plant communities in ancient and strongly weathered soils containing very low levels of available N and P (Laliberté et al. 2013). Broadly speaking, abundant soil resources (e.g. N, P) favour high plant productivity, while low soil resources favour plant species diversity (Laliberté et al. 2012; 2013). The species diversity and dominance can be further shaped by the co-existence of abiotic stress, such as drought and salinity, which favour the colonisation of pioneer plant species, such as halophytes and tolerant leguminous plant species.

The diversity and redundancy of soil, regolith, landform and associated biota underpins functional ecosystem processes and their resilience to cope with dynamic disturbances, such as drought, fire and extreme rainfalls: i.e. the ability to adapt and change for self-reorganisation in response to the disturbances, without losing ecosystem functions (Walker 2020). For example, surface erosion can be significantly alleviated by undulating landforms of diverse topography (e.g. alternate patterns of grass, trees, and shrubs) and heterogenous composition of regolith profile (e.g. variable volumes of gravels and rocks across spatial distance and vertical profile). Artificial landforms of linear designs (e.g. long and straight slopes and dam walls) do not have the diversity of micro-patch landforms to cope with surface erosion, when extreme rainfall occurs. Natural landforms are usually nonlinear in topography and regolith structure.

The diversity of soil biota is closely related to plant species diversity, as they influence soil biogeochemistry. For native plant growth in nutrient limiting soil, both free living bacteria (diazotrophs) and rhizobium-symbiosis provide redundant mechanisms of soil N supply across variable seasonal conditions. Both fire-tolerant and sensitive leguminous species are present in a resilient plant community, so after fire, the tolerant plant species can still fix atmospheric N₂ to restart biomass growth. Plant communities dominated by fast-growing plants would have high resilience but low resistance, while communities dominated by slow-growing plants tend to have low resilience, but high resistance (Díaz & Cabido 2001). This is probably why biodiversity hotspots need good protection from surrounding disturbances caused by human activities, such as mining. Many native plant species in Australia have developed sophisticated microbial-root acquisition and foliar N conserving mechanisms to live in infertile soil of very low levels of available N and P, such as native Banksia and Jarrah species (Lin et al. 2011; Pate et al. 1993) and spinifex in arid landscapes (Winkworth 1967).

3.1 Summary

The regolith (i.e. vertical profile of mineralogy, geochemistry, physical properties) and topographic features of landforms underpins their functionalities in regulating the distribution of water (e.g. deep infiltration versus runoff), nutrients (e.g. P, N?) and biota (e.g. microbes and plant species). The landform diversity and distribution patterns (including vegetation) determine landscape patterns, which are the foundation of ecosystem processes. For example, the landscape patterns and ecohydrological processes are closely coupled, which can in turn be shaped by and regulate plant species distribution (Figure 3). We need to integrate knowledge from landscape ecology into mined landscape rehabilitation.



Figure 3 (A) Natural landforms at Mount Isa formed from rock erosion: the bottom of the hill is colluvial soil and the upper slope is rocky; (B) Created landform from coal mine overburden with topography diversified by dunes of rock mulch to create micro-landform diversity and redundancy, with developing potential of landform process to be integrated into the landscape

4 Mining impacts on terrestrial ecosystems and current limitations of rehabilitation approach

The spatial scale of terrestrial ecosystems impacted by mining activities is usually in the range of 100s–1000s ha, including infrastructure, voids, spoil or overburden dumps, waste rocks and tailings. At a landscape scale, these activities cause significant system fragmentation of terrestrial ecosystems by changing

regolith, landform, and associated biota. We have used deep open cut mining and mine waste storage facilities for our scenario analysis below.

1. Loss of regolith structure and functions and associated topographic features:
 - a. By removing variable proportions of pedolith to saprolith to access ore deposits, such as mining voids of base metal mines, coal mines.
 - b. By addition of non-soil pedolith and saprolite (i.e. mixtures of overburden) on top of the original pedolith, leading to its functional loss, such as in dumps of overburden composed of dispersive clay and waste rocks found at open cut coal mines. In Australia generally, large amounts of dissolved salts are present in the non-soil pedolith and saprolite materials, contributing to secondary salinity (Wilford et al. 2016).
 - c. By placement of mineral wastes from ore or mineral processing, such as tailings and waste rock storage facilities.
2. Loss of landform diversity and redundancy in structure, topography and functional processes, but the addition of artificially engineered landforms with linear design and homogenous structure such as linear slopes and homogenous substrates without coarse materials (e.g. large gravels, rocks).
3. Fragmentation of landscape patterns and interruption of landscape processes (e.g. biogeochemical processes, hydrological processes), leading to the dysfunctional ecological processes at ecosystem level, such as the flow of materials (e.g. salt and sediments), genetic flow (due to the disconnection with natural ecosystems), ecological diversity and redundancy (due to the loss of biota-rich topsoil).

These extensive alterations and disruptions caused by mining activities have posed a great challenge to the rehabilitation of mined landscapes with sustainable and resilient ecosystems. For example, most of the Bowen Basin is considered an alluvial plain which has been shaped by erosion and receiving water-transported salts and sediments, resulting in two contrasting types of landforms: (1) landforms with limited relief and undulating topography and gradients (<5%) and (2) slopes with >5% gradient supported by outcropping quartzose/Permian sandstones (Emmerton et al. 2018; Erskine & Fletcher 2013). However, the Bowen Basin now contains many steep (>10% gradient) elevated (>100 m above the ground level) artificial landforms without the physical support of competent sandstones.

At the domains occupied by overburden dumps, the high loading of salts in these overburden and spoils cannot be easily leached out of the profile without significant changes to physical composition by increasing coarse materials and porous structure in the profile. To change salt-loaded overburden and spoils placed at the surface profile into soil-like substrates, it is necessary to induce solute transport processes which is one of the essential processes in natural soil formation at alluvial plains. However, this process has been interrupted by the changed landforms and the biologically competent topsoils were not properly rescued and conserved in most cases.

The storage dams of reactive waste rocks and tailings across the landscape represent even greater challenges, because they often exhibit mineralogical and geochemical instability, including sulfidic and metallic tailings and acidifying waste rocks. Profound mineral weathering and transformation are required if soil formation at the surface layer is to be activated to develop the pedolith profile (Huang & You 2018; You 2015; You et al. 2018). Ultimately, these kinds of landforms will be shaped by nature forces to be merged into the landscape over decades and centuries. If we recognise this, how can we engineer redundancy and diversity mechanisms in the slope landforms of these waste storage facilities to prevent environmental and ecological damage from occurring? How can we develop methods and techniques to enhance the weathering and hydrogeochemical stabilisation of the waste profile to mitigate environmental risks, simulating natural weathering processes in the development of a pedolith profile? These remain to be investigated in future research.

4.1 Summary

Natural regolith, landforms and landscapes have been shaped by natural forces over many centuries, reaching a dynamic state of adaptiveness and self-regulation, which have developed intrinsic processes and resilience to cope with and adapt to natural disturbances. Mining activities, within a very short period of time, have significantly altered the vertical structure and mineralogical and geochemical properties of land profile (particularly, the pedolith zone where biological activities are located), damaged natural landforms, and created foreign landforms of engineered structure without ecological competence. These have abruptly changed landscape patterns and fragmented and interrupted landscape processes (e.g. hydrology). These changes have damaged or destroyed terrestrial ecosystems in structure and functional processes within a mined landscape. Key limitations of current decision-making and operational practices are:

1. Failure to transit from engineering-based design, planning, methodology and practices largely aiming for uniformity, consistency, efficiency, isolation, and risk management at the mining phase, into ecosystem-based methodology and practices aiming for heterogeneity, diversity, redundancy, connectivity, and ecosystem management.
2. The rehabilitation of legacy landforms caused by mining activities is treated as individual environmental engineering cases, without improving diversity and redundancy as required for ecosystem processes. Limitations consist of long slopes built with texture uniform overburdens, straight and square dam walls, hidden mineralogical changes and geochemical dynamics buried by cover materials.
3. Inadequate knowledge and technology to safely rehabilitate the mine waste landscapes without resorting to the use of large volumes of cover materials, to increase the diversity and redundancy of foreign landform structure and processes, and to regulate and guide landform integration into landscapes for developing ecosystem processes.

Recognising the limitations of environmental engineering, we need to introduce ‘ecological engineering’ into the rehabilitation of mined landscapes for engineering ecosystems as the whole.

5 Ecological engineering to design and develop new ecosystems

5.1 Ecological engineering – the new paradigm of mined landscape rehabilitation

The concept of ‘ecological engineering’ has been around since 1970s, which is defined as ‘the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both’ (Mitsch 2012; Mitsch & Jørgensen 2003). This concept has not yet been adapted into the rehabilitation of mined landscapes in designing, planning, and field operations. A similar concept of ‘ecological restoration’ has been an important influence, due to the default attention of the above-ground rehabilitation of plant communities.

Both concepts are consequentially intertwined, with some duplication:

1. ‘Ecological/ecosystem restoration’ refers to “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed” (Society for Ecological Restoration International 2004). It emphasises the goal to create or restore the best kind of ecosystems similar to the original ones.
2. ‘Ecological engineering’ is broader than ‘ecological restoration’, with the goals to:
 - a. Restore ecosystems that have been substantially disturbed by *human activities* (e.g. mining).
 - b. Develop new sustainable ecosystems capable of delivering both human and ecological values.

3. 'Ecological engineering' emphasises the use of engineering methodology based on ecological and ecosystem principles to design and *develop* new ecosystems with human and ecological values, which may be:
 - a. Different from the original ecosystems (but are similarly sustainable and *resilient* in processes and services)
 - i. In final design shaped by nature, which exhibit a similar magnitude of adaptiveness supported by diverse and redundant ecosystem processes, or
 - ii. In interim design ultimately leading towards the original ecosystems, such as the evolution from pioneer plant communities into keystone species dominant communities resembling the original.
 - b. Original ecosystems with sustainable and resilient structure, processes, and functional services.

Therefore, one of the trajectories of 'ecological engineering' is 'ecosystem restoration' to the original ecosystems, which is the best outcome of 'ecological engineering'.

Key principles of ecological engineering have been summarised as below, based on literature (Huang et al. 2014; Mitsch 2012):

1. *Self-design*: this is the foundation of ecological engineering. It requires the recognition that:
 - a. Nature takes over the design of new ecosystems created by means of engineering inputs.
 - b. Ecosystem structure and processes are self-organising under local climatic conditions and human engineering design should not stop the self-organising processes.
2. *System-specific dynamics*: new ecosystems created by human engineering undergo the initial phase of complex system dynamics and chaos due to interactions and feedbacks within the system structure and processes and external forces.
 - a. Engineered new ecosystems are characteristic of dynamic and complex interactions with and feedbacks of nature forces internally and externally.
 - b. The dynamics of new ecosystems engineered is beyond the prediction of ecological theory which has been developed from old natural ecosystems.
 - c. The understanding how new ecosystems develop along the expected trajectory towards resilient ecosystems requires the understanding of why some structures and processes or the whole system fails to work and enters alternative dynamic states.
3. *System thinking and integration*: engineering methodology on new ecosystem processes are not simply linear cause-effects, but nonlinear system interactions of dominant and modifying processes. It is critical to have system thinking about the consequences of complex feedbacks and interactions, such as:
 - a. Landform roles in driving soil and land development and plant species distribution.
 - b. Landscape patterns driving ecohydrological flow (one of the most critical ecosystem processes).
 - c. Pioneer plant communities in driving soil and land development.
4. *Harnessing nature's energy*: the goal of ecological engineering is to create new ecosystems undergoing self-organisation and self-design under nature forces. The energy required for driving these processes comes from nature, such as solar, wind, hydrological, and biotic (e.g. microbes, roots) energies. For example, the inputs of organic matter are not simply for improving plant productivity, rather stimulating microbial energy for accelerating the weathering of minerals, improving microporosity for harnessing water energy for leaching salts, and developing

water-stable aggregates for resilient soil ecology in tailings and spoils (Huang & You 2018; Wu et al. 2019; You et al. 2018, 2019).

5. *Ecosystem conservation*: it is necessary to adopt ecosystem conservation approach in creating new ecosystems and agroecosystems across mined landscapes, for diverse ecological values for both human and nature benefits. In fact, the sustainability of direct human benefits (e.g. food, water and fibre) from agroecosystems is born within the broad ecological sustainability and values. Ecosystem services and agriculture system services should be integrated, but not mutually exclusive (Garbach et al. 2014).

Mined landscapes have extensive alterations of soil profile (regolith), landforms and landscape patterns, beyond the threshold of natural regeneration and recovery (even with some assistance). Rehabilitation of mined landscapes is essentially undertaken to create new ecosystems with integrated and adaptive structure and processes. Most importantly, new ecosystems created require a time frame (e.g. decades) to develop many key ecosystem processes found in the original ecosystems, such as ecohydrological flow, material flow (e.g. biological nitrogen fixation), and genetic flows within and from surrounding natural ecosystems. However, new ecosystems will not necessarily develop the same species composition and diversity as in the original, though there may be some components of the original biodiversity (Wali 1999).

5.1.1 *Transition from environmental engineering to ecological engineering*

It is recognised that extensive civil and environmental engineering design and methods are required to stabilise altered soil profile and landforms in mined landscapes to contain and manage known environmental risks, such as the stability of waste rock dumps, tailings storage facilities, and mining voids/pits. The resultant landforms bear the characteristics of high levels of energy inputs, engineering consistency and uniformity, containment of landscape and ecosystem processes (e.g. hydrological flow). In the context of ecosystem, the limitations and flaws of many rehabilitation projects may be summarised as below:

1. *Human design*: the priority and emphasis are placed on human power to design ecosystems for today's values, based on transplanting and superimposing concepts and features of the original ecosystems or agroecosystems (e.g. reference sites).
 - a. There is a failure to recognise the self-designing behaviour of ecosystems.
 - b. There is a failure in the transition from uniformity and efficiency to diversity and redundancy in landform and landscape structure and functional processes.
2. *Generic system-design based on modelling and engineering standards*: many landform designs used in rehabilitation are based on generic behaviour and modelling of natural soil, landforms and landscapes, without recognising the mineralogical and geochemical dynamics of overburdens and mine wastes. These have resulted in mismatched assumptions between soil and mine wastes in terms of hydraulic behaviour and hydrological processes. Many TSF and WRD landforms capped based on environmental engineering designs have gradually lapsed into degradation in environmental and ecological outcomes, such as capillary rise of polluting seepage, seepage ponding, contamination of cover soil, and vegetation failure. These cover systems require expensive and ongoing treatment to contain seeping pollutants onsite.
 - a. Hydrological flow is an essential process for transportation of dissolved salts in natural pedogenesis.
 - b. Bioweathering of minerals occur at biointerfaces when moisture is available.
 - c. Mineral weathering and salt co-precipitation change surface energy and hydrophilic behaviour of soil/mineral particles, leading to increased compaction and hydraulic resistance, such as in the unsaturated up-profile of sulfidic tailings and bauxite residues.
3. *Domain-specific thinking*: rehabilitation is domain-specific and the continuation of environmental engineering for managing domain-specific risks without considering the implications of ecological

processes. For example, slope landforms of overburdens and WRD have been shaped for vegetation establishment without increasing the diversity of topographic features.

4. *High energy use*: Engineering methods based on high energy use have been practiced to reconstruct/improve soil conditions, regolith profile, landforms and landscapes, by, for example:
 - a. Importing large volumes of earth materials from offsites by transportation, installing compressed clay and/or geomembranes to suppress weathering processes in tailings, waste rocks, and overburden, for presumed isolation of reactive minerals from infiltrated water and oxygen.
 - b. Introduction of collected seeds from natural ecosystems, rather than natural seed banks in fresh topsoil.
 - c. High inputs in maintenance of the engineered landforms.
5. *Narrow set of values*: rehabilitation of mined landscapes has been (sub)consciously driven towards unfounded priorities of economic land use, culture land use, and/or conservation values, rather than being integrated based on a wide set of ecosystem services. It is important to recognise that agroecosystem services should not just have on-farm benefits, but should be widened to include off-farm benefits and public benefits, such as water flow quantity and quality, carbon sequestration, and pest and weed control (Garbach et al. 2014). Agroecosystem's sustainability is unfounded without the biodiversity of the broad ecosystem of its surroundings.

As a result, it is necessary to shift the thinking, planning and operations from environmental engineering into ecological engineering, to advance rehabilitation of mined landscapes from the last four decades of learning into next four decades of success. To realise this transition, it is necessary to recognise the critical differences between mining phase and rehabilitation phase, in terms of:

1. Landform design requirements: can we relax the footprint limit for reshaping the steep slope of overburden dumps and WRD? This is necessary if we are to increase the diversity and redundancy of landforms for regulating hydrological processes.
2. Ecological requirements in engineering practices: mine sites would need to recognise the knowledge and expertise of environmental engineers are not sufficient and it is necessary to carefully design ecosystem rehabilitation experiments which allow a site to understand the implications of environmental engineering outcomes in the development of ecological processes.
3. System planning and integration across domains: the expected outcome of mined landscape rehabilitation is not the array of individual isolated domains of environmental engineering projects which are dotted across the landscapes, without process connectivity and integration.

Regulators and communities expect that the new ecosystems created in mined landscapes will gradually develop key ecosystem processes and functions, along a trajectory from environmental stability into ecological resilience and sustainability.

6 Designing new ecosystems by integrating ecology with engineering

It is recognised that 'engineering' methods are prescriptive and definitive in operational process, such as land forming and seed sowing, cover systems, drainage installation, and slope stabilisation, which are easily and conveniently adopted into rehabilitation programs. In contrast, 'ecological' methods are descriptive, with an open scope of operational requirements in managing environment risks and regulating ecological processes over an undefined time frame. As a result, it is necessary to integrate ecology into engineering, in design principles, operational processes, and assessment standards.

6.1 Designing and creating new pedolith – eco-engineered pedogenesis in mine wastes

The first challenge in rehabilitation is how to create a range of new regolith profiles with functional pedolith to support desired plant communities. As highlighted previously, deep open cut mining methods have placed much of saprolite and non-soil pedolith on top of land surface, such as the overburden and waste rocks, which may have unstable chemical and physical properties incompatible with plant growth. For example:

1. High salt contents in saprolite profile.
2. Massive and dispersive clays without microporous structure.

The overburdens are parent materials of soil formed in nature, but this process takes a long time without artificial inputs. It is possible to adopt ecological engineering practice to accelerate the soil formation process, by:

1. Increasing the coarse fractions (e.g. rock fragments, carbon rich rejects) to improve macroporosity in the overburden profile, which would stimulate the leaching process of soluble solutes (one of the critical processes of soil formation).
2. Increasing organic matter (e.g. plant litter, mulch) to stimulate microbial activities and mineral weathering and transformation, water-stable aggregate formation.
3. Introducing tolerant pioneer plants for advancing soil formation. Pioneer plants are powerful biological drivers in natural soil formation, which are early colonisers of disturbed landscapes with poor fertility and physical-chemical conditions. The benefits of native pioneer plants have not been acknowledged in rehabilitation of mined landscapes.

These are typical practices of ecological engineering by harnessing low energy inputs to stimulate ecological processes (e.g. microbial activities, root-mineral interactions) and soil formation from tailings and overburdens with low pollution risks (Huang et al. 2014; Huang & You 2018; Wu et al. 2019).

Tailings landscapes represent the extreme difficulty in creating new pedolith profile, since tailings (e.g. Cu, Pb-Zn, bauxite residues, coal tailings) contain many unstable minerals which may undergo weathering and release toxic factors, such as acidity, metal(loid)s, alkalinity, and/or salinity (Huang et al. 2012, 2014). In these cases, a topsoil profile installed over the tailings surface is prone to degradation due to the presence of the toxic factors. This is inevitable even if an elaborate cover design is installed with compressed clay-layer, since abiotic (e.g. localised subsidence) and biotic (e.g. tree roots, termites) will destroy the physical integrity in a relatively short period of time. However, the geochemical risk in the top profile (e.g. 0–100 cm) can be removed if a layer of massively weathered and cemented profile can be formed to play the physical role equivalent to sedimentary rock layer (Huang et al. 2014). For example, a layer of hardpan cemented by in situ formed Fe-Si gel supported native vegetation for >15 years at sulfidic Cu-Pb-Zn tailings under semi-arid climatic conditions (Liu et al. 2019; Nguyen et al. 2022). We have demonstrated in laboratory studies that the weathering and cementation in sulfidic Pb-Zn tailings can be accelerated by stimulating native Fe/S-oxidising bacteria by supplying nutrients (e.g. N, P) (Liu et al. 2021). Further scaling up studies are needed to translate the concept into field feasible technology and methodology, for transforming current practices in tailings rehabilitation at mine sites.

6.2 Designing and creating new landforms by increasing diversity and redundancy for developing soil and land processes

Engineered landforms are a common legacy of mining activities, such as elevated storage facilities for containing waste rocks and tailings, overburden stockpiles, all of which often have linear dimension in slopes. These are contrary to natural landforms which are nonlinear, with high diversity in topographic features and redundancy in physical make-up (e.g. rock distribution). It is recognised that the linear design of the storage facilities (except for historic valley fills) is for operational efficiency and risk management during the active mining phase. However, after the mining operation phase ends and rehabilitation and mine closure starts,

how can we change the linear design of these legacy landforms into nonlinear designs with diversity and redundancy, for developing ecosystem processes leading towards resilience? Several questions are worth discussion here:

1. Existing dam walls are lacking soil and landform diversity and redundancy. Can we use overburden and rocks to add another layer of slopes with a diverse range of physical make-up outside of the dam wall?
2. If so, can regulators allow this by recognising the extra footprint for ecological roles, rather than mining operation?

We need to acknowledge that natural forces will take over the shaping of the dam walls after a mine is closed and maintenance stops. If one day parts of the dam wall weathered away, what would happen with the tailings stored inside? If tailings dams can be transformed with extensive weathering and cementation in the tailings and additional nonlinear slopes outside the current walls, it may significantly improve their resilience in the long-term. In addition, it is essential to define the ecological role and impacts these landforms have upon the wider landscape and new ecosystems need to be designed and developed.

6.3 Designing and creating new ecosystems by landform integration for developing ecosystem processes

Ecosystems covering whole landscapes are composed of diverse soil types and landforms, which drive the distribution of different plant communities. The ecosystem structures require integration to develop ecosystem processes, such as hydrological cycles (e.g. different patterns of water infiltration and surface runoffs), materials flows (e.g. redistribution of organics and mineral sediments), and genetic flows (e.g. species dispersion, colonisation, and plant community evolution). How can we integrate ecological principles into the design and creation of new ecosystems across landscapes and provide connectivity into surrounding natural ecosystems?

1. Recognising soil and land processes drive the development of plant communities in the long-term, can we distribute soil and land types and features spatially when shaping/modifying different domains of a mined landscape? For example, fine textured soil at low lying areas for supporting grassland, while coarse textured and deep profiles are created by admixing rocks for supporting tree species.
2. Recognising water will flow towards and congregate into low lying areas, can we deliberately design water retention landforms for purposely collecting salts released from overburden and waste rock landforms, as a transitional role in developing ecosystems?
3. The development of genetic flow similar to natural ecosystems in the surrounding is highly challenging, since mine sites are deficient in fresh topsoil containing rich seed bank and biota. The role of fresh topsoil in establishing diverse native plant species (especially the understorey species) has been well demonstrated in many rehabilitation sites. Can we create colonies or patches and corridors by creating suitable landforms with fresh topsoil to develop genetic sources across the landscape? Before doing so, we need to investigate in field trials what is the suitable size of such colonises to have an adequate influence on ecosystem resilience.

It is advocated to adopt landscape ecology knowledge and research methodology into the modification and integration of different landforms across the mined landscape, when designing and creating new ecosystems. Field trials should focus on understanding how to modify and shape individual landforms for desired ecological roles within the new ecosystem. For example, what are the minimal diversity of slope design required to support plant communities of trees and understorey plants and underlying hydrological role without erosion risks?

7 Development trajectory of new ecosystems: soil, land, and ecosystem processes

It is recognised that the development of new soil, landforms, and ecosystems is a nonlinear process over many years/decades/centuries. The development journey of new ecosystems in mined landscapes may be broadly generalised into three major phases (Figure 4):

1. Phase 1 – Ecosystem design for environmental stability and ecological potential (short-term – years): this phase is closely related to ecosystem design, including purposeful diversification of soil properties, landforms and landscape processes. The design integrates the methodology of environmental engineering and ecological principles, for lowering environmental risks and initiate soil and land processes and vegetation distribution. In a created ecosystem, landforms at different domains are expected to interact with each other to develop integrated landscape processes. The design should avoid the expectation to contain environmental risks through isolation.

For example, geochemical risks of tailings may be significantly lowered by stimulating biological weathering of reactive minerals in tailings. Salt loads in overburden may be significantly reduced by enhancing leaching through admixing coarse materials into fine textured materials. The leaching and some degree of erosion would occur at elevated domains (e.g. various dumps and storage facilities), sending solutes downstream. Do we design specific landforms (e.g. temporary wetlands) to enhance and regulate this process in a short term or ignore the process?

In alluvial plains, undulating landforms are formed by the distribution of unconsolidated sediments and fine textured substrates, while steep and elevated landforms have resulted from resistant folded sediments, duricrusts and coarse-grained and resistant sedimentary rocks (Emmerton et al. 2018). This gives rise to the question that it is perhaps necessary to modify the overburden slopes with competent waste rocks to regulate solute and water transport processes and assist the development of diversity and redundancy of micro-landforms (Figure 3).

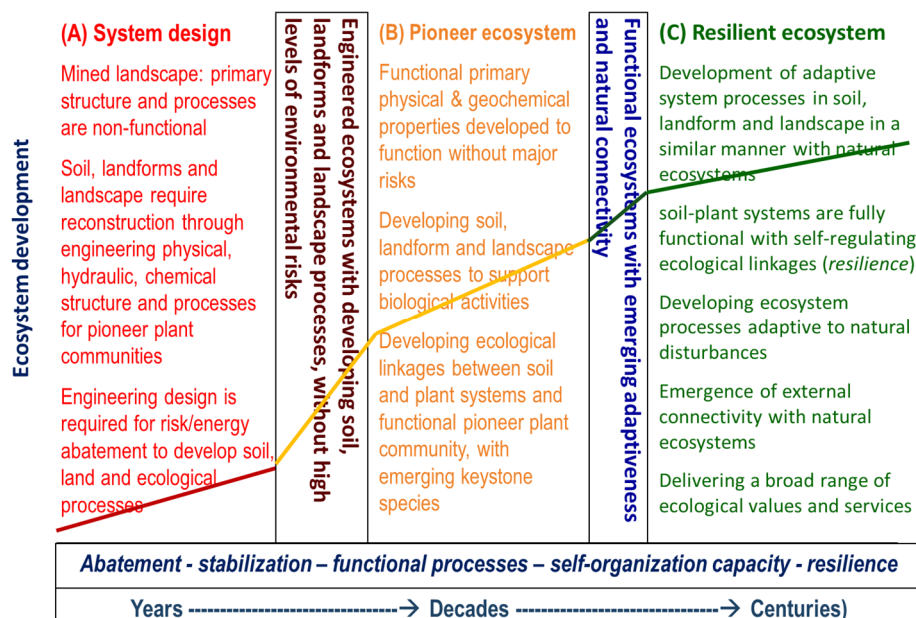


Figure 4 Conceptual trajectory of new ecosystem development created for rehabilitating mined landscapes. The red line indicates the high environmental risk and uncertainties. The yellow line indicates the development of soil and land stability with progressive establishment of pioneering plant communities, which may still have risks of land degradation and limitations of soil and plant ecological processes. The green line indicates the emergence and development of self-regulating soil-plant processes and functions, supporting the transition from pioneer into keystone plant species and the development of adaptive ecosystem processes

2. Phase 2 – pioneer (or transitional) ecosystem (intermediate term – decades). This phase results from the design and practices to create a new ecosystem, with developing properties and functions of soil and landforms and coupled plant communities (e.g. Wali 1999). Ecosystem management would be expected for regulating and adjusting localised soil-land properties and processes, based on identified patterns and ecological criteria. The minimal characteristics of this phase may include:
 - a. Created soil and landforms have developed minimal physical and chemical properties to support the establishment of pioneer plant communities, which have a variety of pioneer plant species and some tolerant keystone plant species.
 - b. Variable development rates of newly created soil and landforms at different domains would have started to differentiate the species composition of plant communities across the landscape.
 - c. Patterns of dynamic solute and water transport processes may have appeared to indicate interactions of different landforms and domains.
3. Phase 3 – resilient ecosystem emergence (long-term – many decades to centuries). The created ecosystems have started to exhibit similar responsiveness and adaptiveness to natural disturbances, in plant community evolution and ecosystem processes, such as flash flooding, bush fire, and/or prolonged dry seasons. The minimal characteristics of emerging resilience may include:
 - a. Plant communities exhibit the evolution of species diversity and functional groups to sustain ecosystem processes, in couple with soil biota composition and functionalities, which will be shaped by changing climate. For example, as local climate shifts from moderate rainfall to extremely dry climate, plant communities are expected to gain plant species (including leguminous plants) of high water and nitrogen use efficiency. Local soils may develop drought tolerant microbial communities, such as biocrusts and fungal communities, to sustain the biogeochemical cycle.
 - b. Genetic flow and connectivity with natural ecosystems in the surrounding have sufficiently developed to gain genetic resources such as plant species, microbes and small faunas.
 - c. Qualitative and quantitative values of ecosystem functions are comparable with natural ecosystems in the surrounding.

The above discussions are by no means comprehensive and only serve as a brief discussion. It is acknowledged that details are to be developed for definitive framework of key attributes about the development of each of the three phases. The frameworks should be further tested according to ecosystem types specific to mining impacts and climatic conditions. These should be systematically investigated in field-based trials designed according to ecological engineering principles and practices.

8 Assessment criteria of new ecosystem development

There is no doubt that newly created ecosystems will take many decades to develop soil, land, and ecosystem processes (see Figure 5). It is difficult to directly superimpose key attributes of natural ecosystems (i.e. so-called reference sites) onto the newly created ecosystems, for judging rapid rehabilitation success. It is advocated to develop trajectory-based completion criteria to evaluate the development of ecological functions and ecosystem processes, rather than focusing on superficially comparing vegetation similarity while ignoring the underpinning soil and land development processes.

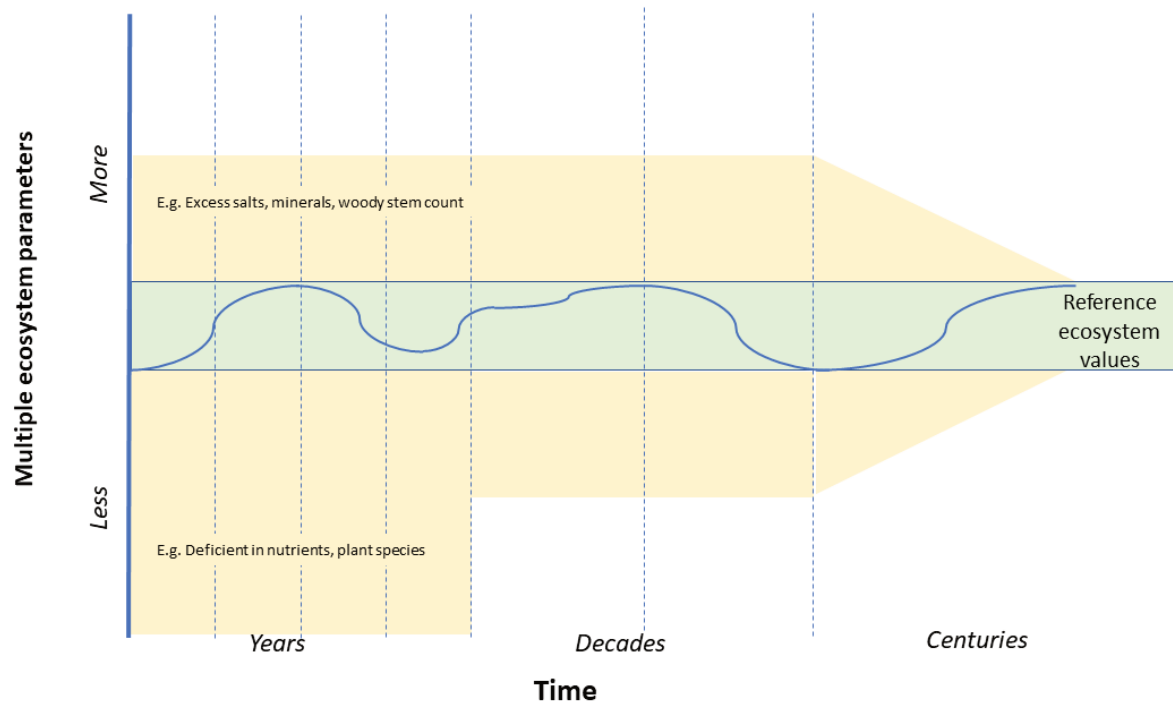


Figure 5 Reference site parameters can be used to guide management interventions if the goal is to create a resilient ecosystem on rehabilitated mined land. There are multiple points (vertical dotted lines) where interim criteria should be assessed to align with the proposed trajectory

Resilience is the ability to adapt and change, to reorganise, while coping with disturbance (Walker 2020). A resilient system responds to a disturbance by changing the relative amounts of its different parts and how they interact, thereby changing the way it functions. An ecosystem may learn from a disturbance (e.g. prolonged dry seasons) to develop water and nutrient-conserving plant species and microbial communities in soil, which is to be able to better cope with a similar disturbance (e.g. recurring drought) in the future. For example, climate changes over the next 50–70 years suggest that global temperatures may increase and atmospheric CO₂ concentrations may rise, resilient ecosystems must be capable of adapting plant communities in species composition to drought tolerant ones (Walker 2020), with increasing roles of fungi in litter decomposition and nutrient cycling (Wardle et al. 2004). This kind of plant community evolution requires functional genetic flow to be developed in the new ecosystems created in mined landscapes, one of the critical ecosystem processes.

8.1 Perspective

Rehabilitation of resilient ecosystems in mined landscapes is not a linear process of simply preparing land and sowing a variety of native seeds. This does not appear to work on a regular basis, with one great leap forward to reach resilient ecosystems similar to native ones. It requires a holistic process of systematic design and methodology integrating ecology with engineering when creating new ecosystems. It is not simply a collection of individually isolated environmental engineering projects across different domains of mined landscapes. If the development of resilient ecosystems is the final goal of rehabilitation of mined landscapes, there are several key changes to be made by industry sector and practitioners, regulators, and researchers.

1. *Industry sectors and practitioners*: must recognise that rehabilitation of new ecosystems requires the fundamental transition from environmental engineering into ecological engineering, including system analysis and field methodology in designing and creating new ecosystems. During mining operation, environmental engineering aims for risk management, production and management efficiency, and operational standardisation and consistency. In contrast, creating new ecosystems requires risk abatement (i.e. depletion of risk energy in various foreign landforms), elevated soil

and landform diversity, and landform interactions and integration, leading to the development of ecosystem processes. The decision-making should take into consideration soil formation and land development processes, soil-land development driven plant community composition and diversity, landscape ecology, and ecosystem processes. The uptake of agronomic knowledge and methodology must be carefully balanced within the context of ecosystem development. The planning of agroecosystem for economic land use should be considered within the broad conservation value of new ecosystems to be developed. After all, the sustainability and resilience of agroecosystems are closely linked to biodiversity of the broad ecosystem where the agroecosystems are located within. The minerals sector should fund long-term (multi-decades) and multidisciplinary field trials at a system scale.

2. *Regulators*: may have to consider different sets of regulations and standards for regulating footprints for (a) mining production and (b) rehabilitation of mined landscapes with resilient new ecosystems. It is important for miners to conserve land areas to be impacted by mining activities during production phase. However, during rehabilitation phase, the expansion of footprint area of storage facilities may be necessary for increasing landform diversity and redundancy, such as adding additional layers of nonlinear topography for supporting diverse plant communities. Developing diverse types of soils and landforms is critical to the development of plant communities and species diversity.

In addition, the assessment criteria may need to reflect the timeline of new ecosystem development, with the focus on environmental risks and development trajectory of the new ecosystem. The critical role of new ecosystem management may be integrated into the holistic process of rehabilitation assessment. Simplistic comparison between the new ecosystem created and natural ecosystems (so called reference sites) should be limited to parameters that may be meaningful in the long-term (Figure 5). Most importantly, the assessment should focus on the developmental trajectory of soil and land processes required to drive the development of plant communities and resilient ecosystem processes for coping with natural disturbances (Figure 4 and 5).

1. *Researchers*: multidisciplinary fields should collaborate to design and implement long-term landform-scale field trials. These are required to understand the complex interactions among soil development, land processes and plant community development and evolution. A vast volume of literature is available about many key aspects involved in rehabilitation of new ecosystems, such as soil and land development processes, landform structure and hydraulic functions, the relationship between soil-plant development and plant community evolution, the relationship between biodiversity and agroecosystem sustainability, native plant ecology, and other relevant topic areas. We need to learn from these and avoid reinventing wheels.
2. *Educators*: are required to train the next generation of workforce and researchers in the field of ecological engineering, as we need a large number of rehabilitation researchers and practitioners in many decades to come. As far as we know, no universities in Australia offer formal training in the field of ecological engineering, despite many universities offering environmental engineering and management courses.

Acknowledgement

The present paper are the views of the authors, that have resulted from the authors' experience and observations, and discussions with colleagues and anonymous practitioners. It serves as stimulus to discuss the way forward for rehabilitating resilient ecosystems in mined landscapes. It is by no means a comprehensive literature review.

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