A review of landscape rehabilitation frameworks in ecosystem engineering for mine closure

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Abstract

Mining causes changes to the environment and rehabilitation is necessary at mine closure. There is a lack of appropriate frameworks for mine site rehabilitation. In most cases, restoring the mine to previous conditions is challenging. Alternatively, mining companies can engineer ecosystems to suit new site conditions and aim for a self-sustaining and resilient ecosystem. In ecosystem design there should be consideration of the four key dimensions of any ecosystem; landscape, function, structure and composition (LFSC). Alcoa's Bauxite mines and Barrick (Cowal) Limited's Gold Mine have considered LFSC in their rehabilitation practices. From this, a framework based on LFSC is proposed as a means of planning, undertaking and monitoring mine rehabilitation, which together aim for a self-sustaining and resilient ecosystem. Elements of this framework are being utilised in the industry, and are supported by research. The framework could be used as an industry standard, utilised by regulatory bodies and potentially used in conjunction with other models and in other rehabilitation environments.

1 Introduction

Major ecosystem disruption during mining causes difficulties in restoring the area to a pre-mine landscape. Mining practices can result in loss of vegetation and fauna, soil degradation, altered hydrology and landforms. Changes to landscape, water sources and soil properties (Bradshaw 1983), may mean that the original ecosystem may not be suited to the new conditions (Bradshaw 1983; Gardner and Bell 2007; Hobbs and Harris 2001). Therefore, it becomes problematic to restore the ecosystem that was present pre-mining. As an alternative, an 'engineered ecosystem' is created in a post-mine landscape (Bradshaw 1983; Bradshaw and Huttl 2001). Engineered ecosystems are designed to evolve with the new conditions on site. The aim of an engineered ecosystem is to create a system which is self-sustaining and resilient (Bradshaw 1983; Elmqvist *et al.* 2003; Gardner and Bell 2007; Grant *et al.* 2007; Ruiz-Jaen and Aide 2005; Thompson and Thompson 2004). For an ecosystem to survive long term without human interference, it must be resilient to variability, including climate, by promoting mechanisms such as biodiversity (Elmqvist *et al.* 2003). It must also be able to look after itself in the long term, including sufficient nutrient and water cycling and regeneration (Elmqvist *et al.* 2003; Grant *et al.* 2007). To achieve a self-sustaining and resilient ecosystem, complexity and ecosystem hierarchy need to be addressed.

Hierarchical complexity drives a resilient and self-sustaining ecosystem, yet this is also difficult to design and engineer. Bradshaw and Huttl (2001) argue that successful restoration of a minesite is dependant on whole of ecosystem rehabilitation. Planning for abiotic and biotic factors and the dynamics between them is important for successful rehabilitation (Bradshaw 1984; Hobbs and Harris 2001). A ecological hierarchy (Figure 1) demonstrates the complex dynamics of ecosystem components and their reliance on each other (Dale and Beyeler 2001). Plants and animals are reliant on soil and water, whilst soil and water will not exist without landform, geology and climate. Therefore, with more components there are also more interactions and thus increase in the complexity of the ecosystem (Dale and Beyeler 2001; Spain *et al.* 2006). These dynamic interactions and complexity make the ecosystem resilient to changes and able to support itself. This complexity can be difficult in the process of designing and engineering an ecosystem (Bradshaw and Huttl

2001). Without a reference ecosystem as an aim for mine rehabilitation, it is difficult to determine what components are required and what complexity is necessary for the engineered ecosystem.

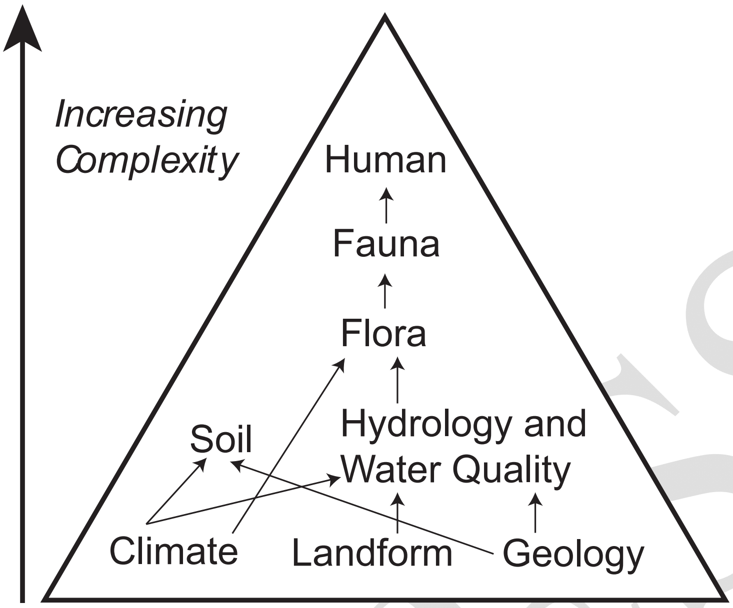

Figure 1 Hierarchy of ecosystem components leading to increased complexity. Adapted from Jeanes (1998)

Previous research breaks the complexity of ecosystems into four key features: landscape, function, structure and composition (LFSC) (Elmqvist *et al.* 2003; Loch *et al.* 2006; Ruiz-Jaen and Aide 2005; Tongway and Hindley 2004). LFSC simplifies ecosystem components (Figure 1) into four key features that can be found in any ecosystem (Figure 2). Like Figure 1, it also demonstrates ecological hierarchy, dynamics and increasing complexity (Dale and Beyeler 2001). Together all the key features form a complex, self-sustaining and resilient ecosystem.

LFSC considers all ecosystem components in any type of ecosystem, and is therefore ecosystem independent. Components of any ecosystem can be included into each of the key features. Landscape includes landform features, water sources, climate and geology. Function considers biogeochemical cycling; the cycles in the system which maintain biological life, including water and nutrient cycles (Ruiz-Jaen and Aide 2005; Tongway 1990). Structure considers the components of habitat, succession and productivity (Ruiz-Jaen and Aide 2005), such as soil, litter, vegetation structure, habitat features (logs, rocks etc) and macro and micro organisms. Composition is the biodiversity and resilience of the system (Ruiz-Jaen and Aide 2005). LFSC can be used in the broad sense to describe any ecosystem, or can include discreet ecosystem components within the framework. This may include describing forest, agricultural, aquatic or other natural or man made environments. It also has the potential to describe an engineered ecosystem.

Frameworks for rehabilitation must consider the severity of landscape change. Frameworks can be used to simplify planning and implementation of mine rehabilitation. State and Transition Models (STM) have previously been considered by Alcoa in mine rehabilitation (Grant 2006; Koch 2007b). STM's are designed using a reference ecosystem and rehabilitation planning and practice aims towards the reference conditions (Grant 2006). There is varied research in STM's usefulness for understanding rehabilitation in disturbed ecosystems. Yates and Hobbs (1997) considered that STM's can demonstrate multiple paths for succession towards the aimed ecosystem; this being most important in areas with disturbance. Grant (Grant 2006) also found that STM's could be used in bauxite mine rehabilitation. When a STM was used successionally with a trajectory towards a reference ecosystem (Jarrah Forest), it was able to demonstrate undesirable rehabilitation pathways and allowed for adaptive management. However, Gardner and Bell (2007) discuss that heavy disturbance from bauxite mining often means true reference ecosystem rehabilitation can not be achieved, and that a self-sustaining ecosystem should be the aim. This was supported by Koch (2007) who suggested that the end ecosystem will not reach reference ecosystem conditions due to specific changes in climate, hydrology and flora composition as a result of bauxite mining or other environmental changes, such as climate change. This implies that STM's can be used in areas with a small amount of disturbance or can be used as an indicator and adaptive management tool in context of successional change. However, STM's are not as useful in rehabilitation contexts where significant disturbance has occurred and trajectory ecosystems are unknown.

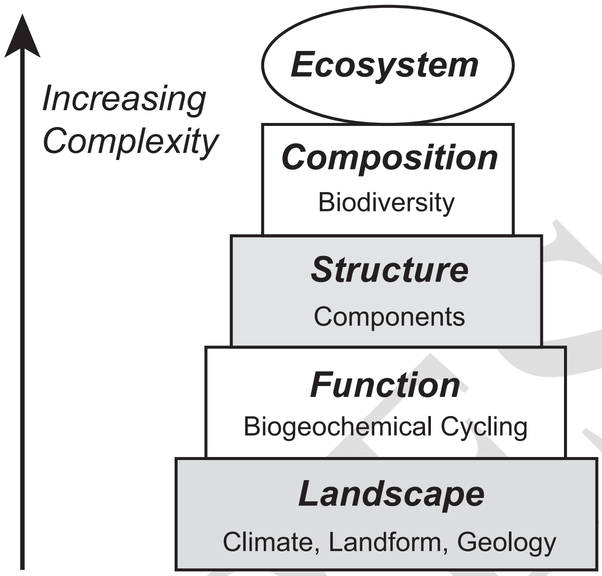

Figure 2 LFSC building blocks for increasing complexity and a self-sustaining and resilient ecosystem (Elmqvist *et al.* 2003; Ruiz-Jaen and Aide 2005; Tongway 2005; Tongway and Hindley 2004)

LFSC has the potential to be used as a framework in mine rehabilitation. Spain et al. (2006) describes the 'uncertainty of trajectory' that can occur when rehabilitating. As engineered ecosystems have no specific reference ecosystem to use in the design process, recreating complexity of a system with no baseline can be problematic. Problems occur in the design, implementation and determining the end point of the ecosystem. This is due to the lack of a reference condition in which rehabilitated conditions can be compared. Spain et al. (2006) suggests undertaking stages of rehabilitation as one option to limit the risks of failed attempts. Therefore, mine rehabilitation requires a model that can be undertaken in stages, is flexible, adaptable, and can be implemented without a specific reference ecosystem. Utilising LFSC in understanding ecosystem complexity can potentially simplify the design process for engineering ecosystems. LFSC has the potential to be used as a tool in ecosystem design, due to ecosystem specific independence and adaptability to non-specific end point conditions. Tongway and Hindley (2004), Tongway (2005), Ludwig et al. (2003), along with Loch et al.(2006; 2008) have previously identified frameworks that include aspects of LFSC and tiered or step approaches as a means of simplifying rehabilitation planning, practice and monitoring. Therefore, a framework based on LFSC principles may potentially be viable for use in a mine rehabilitation context. To demonstrate how mines are currently considering LFSC in their rehabilitation practices, two Australian case studies will be reviewed; Alcoa Bauxite Mines in Western Australia and Barrick (Cowal) Limited's Gold Mine in New South Wales. These examples will also demonstrate if a framework from LFSC principles would be effective for rehabilitation planning and practice within the Australian mining industry. The LFSC framework will then be introduced, along with suggested monitoring, considerations and benefits.

2 LFSC in rehabilitation practice

2.1 Alcoa Bauxite Mines

Through in-house and independent research, Alcoa bauxite mines in Western Australia have shown to consider LFSC in rehabilitation planning, practices and monitoring. Although Alcoa do not use a framework based on LFSC as part of their rehabilitation strategy, they inherently consider aspects of LFSC in their planning and practices. Alcoa includes practical steps to reshape the landscape, minimal stockpiling of soil to retain functionality, retention of habitat features, revegetation for structure and composition, and monitoring. Prior to mining, soil was stripped and stockpiled in small piles to maintain biological activity (Jasper 2007; Koch 2007). This was along with retention of wood and rocky debris for habitat reconstruction (Koch 2007). After mining the site was reshaped to fit natural landforms (Gardner and Bell 2007), with topsoil respread over the landscape. Erosion protection was considered in respreading soil (Koch 2007) to ensure landform stability. Restoring functionality to the site included considering the use of fertilisers, N-fixing species and leaf litter in restoring nutrient cycling (Grant *et al.* 2007), as well as considering soil biology (Bell *et al.* 2003; Jasper 2007). Structure and composition was considered through research into soil seed stores, propagation of species, restoring coarse woody debris and rock habitats (Gardner and Bell 2007). Alcoa uses a range of LFSC indicators as part of their monitoring program. This includes use of Landscape Function Analysis (Tongway and Hindley 2004), chemical and biological nutrient cycling indices (Grant *et al.* 2007; Majer *et al.* 2007) and species that form part of Structure and Composition (Koch 2007b; Koch and Hobbs 2007).

2.2 Barrick Cowal Gold Mine

Barrick (Cowal) Limited's Gold Mine (CGM) also considers LFSC principles in rehabilitation. CGM is located near West Wyalong, in New South Wales, Australia. Like Alcoa, mine rehabilitation practices outlined in CGM's plans (Ryan 1998) naturally consider LFSC, without specifically using a LFSC framework. CGM is actively researching geotechnical stabilisation and soil functionality, whilst considering structure and composition in the long-term. Research undertaken by Summerfield (2006) considered elements of landscape by determining methods of ecological and physical landform stabilisation. Smits (2008) considered improving both landscape and functionality of the site through the application of soil mulch amendments. Indices of functionality were determined using Landscape Function Analysis and landscape stability measured with rill surveys (Tongway and Hindley 2004). The rehabilitation practices aimed to reduce localised erosion, and improve nutrient and water cycling for revegetation, therefore improving landscape stability and functionality of the site (Smits *et al.* 2010). There is continued research into restoring ecosystem functions (Drake *et al.* 2010a) and how to measure indicators of functionality in altered soils (Drake *et al.* 2010b) on trial rehabilitation sites. Other internal and external work has been undertaken on site to consider landform, including reports and research into the stability of landforms, water ways and considering climatic effects. The long-term rehabilitation plans of the site include consideration of structural and compositional ecosystem components (Ryan 1999). This includes the preservation of surrounding habitat, recreating habitat features and a faunal management plan during mine operation for preservation of native fauna. Endemic flora species from the site have been recorded, with seed collection and propagation trials underway.

Both of these case studies demonstrate inherent consideration of LFSC principles in mine rehabilitation planning and practice. The mines are using principles of LFSC within their own rehabilitation strategies. This is independent of differences in mining practices, environment, and framework. The use of the principles by the mines demonstrates that LFSC has the potential to be used as a framework in different landscapes and under individual mine rehabilitation conditions. Therefore, formalising a framework using LFSC principles is possible within a mine rehabilitation context.

3 A framework for rehabilitation

3.1 LFSC framework

From LFSC principles, a practical three-tiered framework can be developed for mine rehabilitation. A rehabilitation framework (Figure 3) has been adapted from Tongway (2005) to include planning, practical stages of rehabilitation, monitoring and adaptive management. Stages include, 1) Geotechnical, 2) Function, 3) Composition and Structure. The overall goal of the three-stages is for the new ecosystem to adapt to the environment and reach a self-sustaining and resilient ecosystem. The LFSC framework for rehabilitation is designed to be successionally implemented over time and can be used to plan and implement rehabilitation at all stages of mining; proposal, operational, cessation. The framework can be filled out according to site-specific conditions. During the mines operation, the framework can be used for implementation through a series of stages. Hobbs and Harris (2001) as well as Loch and Lowe (2008) discuss the need for stages in rehabilitation. Each stage acts as a building block, or hierarchy of complexity in an ecosystem, towards the goal ecosystem.

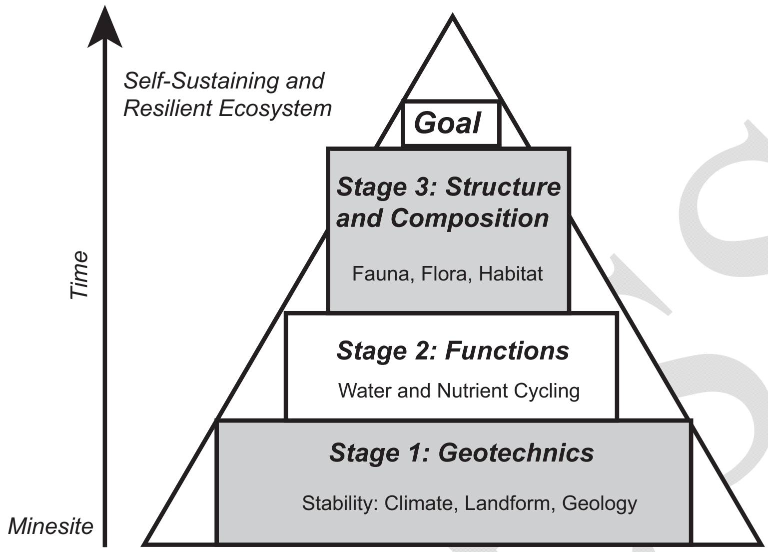

Figure 3 Ecosystem Dimensions (LFSC) as a Framework for Rehabilitation. Adapted from Tongway (2005).

Each stage of LFSC improves conditions towards the aim of achieving a self-sustaining and resilient ecosystem. When using the LFSC Framework, the Geotechnical Stage concentrates on stabilising the mined landscape. Unstable landscapes mean continual loss of resources including soil, nutrient, water loss and continual biological degradation. The continual flows and loss of resources to external environment limits biogeochemical cycling, and thus limits establishment of flora and fauna (Tongway 1990). Therefore, stability of the site is the crucial first stage of rehabilitation, before biology can be reintroduced (Tongway and Hindley 2003). Site stabilisation may include stability of man-made structures, reinstatement of water and landform features, consideration of changes in local climate (drought, microclimate), and changes in exposing geology to climatic features (AMD, salinity) and altered hydrology (ground and surface water interactions). Once the site is stable, functions can be reintroduced (Functional Stage). Biogeochemical cycling on the site can be kick-started by respreading soil and utilising organic and chemical amendments (Carroll *et al.* 2000; Cox and Wheland 2000; Grigg *et al.* 2006; Schwenke *et al.* 2001b). Biological inoculants (Jasper 2007), cover crops (Summerfield 2006), N-fixing species (Gardner and Bell 2007; Grant *et al.* 2007) can all be considered in promoting nutrient cycling. When there is sufficient water and plant available nutrient pools, the Structure and Composition Stage can be undertaken. This includes revegetation, restoring habitat features, reintroducing fauna, improving structural components and biodiversity. As each stage is undertaken, the ecosystem becomes more complex, and is closer to being a self-sustaining and resilient ecosystem. However, determining when the goal has been achieved requires monitoring, evaluation and adaptive management.

3.2 Monitoring, evaluation and adaptive management of framework

Monitoring, evaluation and adaptive management is critical in mine rehabilitation. Previous research has identified the need for a systematic method for monitoring, such as a framework, that covers all ecosystem features and aims at demonstrating a self-sustaining and resilient ecosystem (Thompson and Thompson 2004). Rehabilitation, mining operations and monitoring, evaluation and adaptive management (MEAM) should be undertaken concurrently in the lifecycle of the mine (Figure 4). Monitoring should also be used to determine the effectiveness of rehabilitation. This can be built into the framework for mine rehabilitation.

Goals or Key Performance Indicators (KPI's) (Loch *et al.* 2006) for each stage of the LFSC framework could be used as an indicator for effectiveness of rehabilitation. Ludwig et al. (2003), Ruiz-Jaen and Aide (2005) and Dale and Beyeler (2001) have previously suggested using surrogates of LFSC in monitoring. This has also been implemented by Alcoa (Koch and Hobbs 2007), with two indicators chosen from Function, Structure and Composition. The exact tools chosen for monitoring would be site specific, and based on goals or KPI's of each stage (Loch *et al.* 2006). An example of possible indices chosen for monitoring includes indicators of stability in Stage One. This may include indicators of erosion, water quality, soil stability and run-off control, all measured over time (Loch *et al.* 2006). The information collected from monitoring can then be evaluated to demonstrate the effectiveness of rehabilitation, the need to re-evaluate and reconsider practices, and if the site is ready for the implementation of the next stage. This allows for adaptive management and ensures the most effective methods for rehabilitation are being undertaken.

Monitoring would become more complex over time, and together would demonstrate rehabilitation success. As additional stages of rehabilitation are undertaken, additional monitoring would also occur. Additional monitoring may include Landscape Function Analysis for Functionality (Tongway and Hindley 2004), biodiversity and structural complexity surveys for Structure and Composition, such as Ecosystem Function Analysis (Lacy et al. 2010; Tongway and Hindley 2003) or defined fauna surveying (Thompson and Thompson ND). The combined monitoring and evaluation would aim to demonstrate a) if the ecosystem is able to support itself without human interference and b) that it is able to be resilient to changes. Loch et al. (2006) consider that when all KPI's or goals are met, that the site has been successfully rehabilitated. Similarly, when all goals for the LFSC framework have been met, the site has been successfully rehabilitated.

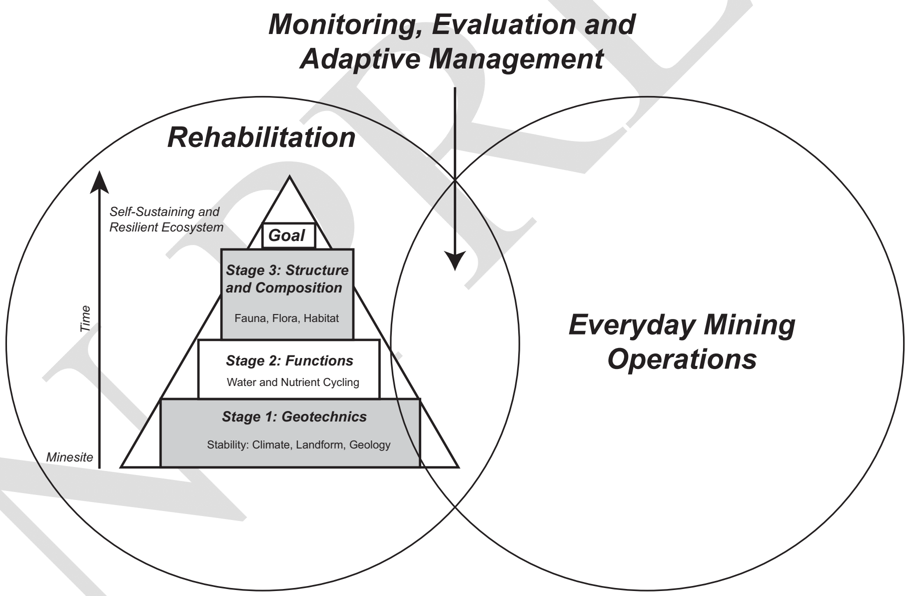

Figure 4 Rehabilitation, Mine Operations and Monitoring and Adaptive Management (MEAM) should be undertaken simultaneously. Adapted from Tongway (2005).

4 Considerations and benefits

There are both benefits and considerations that result from the potential implementation of a LFSC framework within the mine industry. The need for a framework which is independent of ecosystem has been previously identified (Hobbs and Harris 2001; Koch and Hobbs 2007; Loch *et al.* 2006; Loch and Lowe 2008; Tongway and Hindley 2004) and the case studies (CGM and Alcoa) demonstrates that the LFSC framework supports current Australian mining rehabilitation practice. Regulators in Australia have been considering a standard approach to mine rehabilitation, monitoring and success of rehabilitation (Thompson and Thompson 2004). The mine closure strategies by Australian and New Zealand Minerals Councils (2000) and the Australian Federal Government (DITR 2006) are an example of government and industry beginning to consider the need for formalising approaches to staged rehabilitation and closure.

The LFSC framework is independent of environment and end-points, promotes planning, practice and monitoring. It also has the potential to provide consistency throughout the industry and provide a basis for continued innovation. Koch (2007) demonstrates the need for adaptive management in a mine context for ensuring successful rehabilitation. The ongoing MEAM process means practices can be adapted to ensure successful rehabilitation and consider new research and data. The framework can be used for a whole of site approach, be implemented over time, as well as being used on particular areas of the mine. LFSC frameworks can also be used in conjunction with modelling and could form part Bayesian networks, post-mining land use models (Soltanmohammadi *et al.* 2010), Natural Resource Damage Assessment for remediation and rehabilitation (Burger 2008) and other modelling tools. The LFSC framework also has the potential to be developed into a Decision Support System for mine rehabilitation planning and practices, expanding on work such as Chen et al. (2007) or Metago's Sustainability-Based Mine Closure Framework (McPhail and George 2010). Due to the frameworks independence from specific ecosystems, it can be utilised in a range of restoration and rehabilitation activities.

Although the Framework is non-site specific, individual site research is critical. Site research would include planning; defining ecosystem components as part of the stages in the framework; rehabilitation practices; and discreet goals for monitoring. Determining parts of the framework should be undertaken as part of ongoing planning and adaptive management, with in-house and independent research and feedback from monitoring. Considerations should be made regarding interlinking components within the framework stages. For example, research has shown that vegetation can be used in stabilisation, functions and structure/composition (Koch 2007b; Loch 2000; Smits *et al.* 2010). Therefore, the type of practices undertaken may help in achieving several goals within each Stage of the framework. However, in some cases practices may interfere in later rehabilitation stages. For example, cover-crop species used may outcompete or cause weed problems for native plants (Huxtable *et al.* 2005). Economic, cost effectiveness and cultural aspects are not addressed in the framework, and will need to be considered in rehabilitation planning (Spain *et al.* 2006). Further development of the framework is necessary to include more specific steps, such as Worrall *et al.* (2009) or current industry frameworks (Australian and New Zealand Minerals and Energy Council and Minerals Council of Australia 2000). This would include case study use of the framework, implementation with other tools, and consideration of economic and social aspects.

5 Conclusion

There needs to be a rehabilitation framework available to the mining industry that considers flexibility, staged implementation, monitoring and adaptive management, and is ecosystem non-specific. Current rehabilitation frameworks and methods do not always consider the establishment and design of an engineered ecosystem. Frameworks should consider ecosystem complexity and significant changes to the environment as a result of mining practices. Key features of ecosystems include Landscape, Function, Structure and Composition (LFSC). These four key features can be found in any ecosystem, and are independent of environment. Barrick (Cowal) Limited's Gold Mine and Alcoa's Western Australia bauxite mines have demonstrated the use of LFSC principles in rehabilitation plans and practice. This demonstrates that mines are already inherently considering LFSC and we can formalise approaches through the development of a 3-Stage Framework for Rehabilitation. This includes a Geotechnical, Functional, and Structure and Compositional stages for planning, practice, monitoring and evaluation. All stages build on each other, with the final outcome being a self-sustaining and resilient ecosystem. Monitoring and evaluation through use of the framework is critical in understanding the success of rehabilitation. This allows for adaptive management and drives rehabilitation success. Both previous research and the mining industry support the use of LFSC in rehabilitation. Benefits of framework implementation include industry consistency, use of models and ongoing research, flexibility and monitoring of goals. LFSC frameworks have the potential to be developed as a tool for mining and other landscape rehabilitation and restoration activities.

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