Northern mine sites are (probably) novel ecosystems... Now what?

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ABSTRACT

This analysis seeks to situate current and anticipated challenges associated with ecological stewardship with an emphasis on biotic and abiotic limitations for ecosystem development. Echoing wider opinions regarding the management of degraded landscapes, a significant development across the field of restoration ecology is the acknowledgement that highly assertive disturbances, such as mining, can (and often do) cause irreversible effects to natural landscapes leading to the emergence of novel ecosystems. This workshop paper briefly summarizes theoretical underpinnings of novel ecosystems, whereas the associated presentation examines examples of novelty among mine sites and the limitations they pose to 'natural' ecological restoration.

1. Introduction

Mining of minerals and metals has historically represented a major component of the Yukon and Northwest Territories' natural resources economy. Although very few new mining developments appear to be slated for the near future, the region's mining legacy and long-term environmental burden still represents a central priority for land management. In this regard, reclamation of mined land generally aims to achieve safe, stable and productive end-land uses[1] where the mining industry mostly embraces post-mining environmental stewardship and mine closure criteria that lead toward timely relinquishment. However, when viewed in its entirety (i.e., from pre-mining development, to mining and refinery, and ultimately post-mining landscape reconstruction; Figure 1), the challenge of mining and subsequent environmental puzzle of reclaiming affected lands reveals itself to be profound. Accordingly, life-of-mine planning approaches that seek to incorporate physical, financial and social requirements for mine closure even at the earliest stages of permitting and development may not always account for irreversible effects to the natural landscape.

Despite a few notable examples of successful ecological recovery following mining worldwide[2], ecological restoration inevitably becomes more difficult with increasing size and/or severity of the disturbance and most mining activities are sufficiently severe, extensive and long-lasting that critical physical and biological characteristics (Table 1) of the original landscape are drastically altered (Mulligan 1996; Tibbett 2010). Where open-pits, extensive overburden or waste rock, and tailings persist within the landscape, very few reconstructed mined landscapes may ever resemble the pre-disturbance condition (Ludwig et al. 2003). Hence, veritable rehabilitation, reclamation or restoration (depending on jurisdiction) can seldom be claimed unless environments are amenable to plant growth and restoration work is intensive. And yet, regulators (perhaps under pressure from public expectations for timely mine closure; Burton et al. 2012) frequently require that the post-disturbance mining environment be returned and bear close semblance to its pre-disturbance level of composition, structure and functionality. This requirement has sometimes resulted in disjunction between the social and biological expectations for mine sites and the limitation(s) of ecosystem recovery (Worall et al. 2009; Soltanmohammadi et al. 2010; Van Kooten 2011; Burton et al. 2012; Glenn et al. 2014; Hodge 2014). This reality is especially concerning for the planning and implementation of land reclamation following mining in north-western Canada and USA (as elsewhere) where the pre-disturbance or natural ecosystems (in this case boreal cordillera and taiga cordillera systems) may reflect a 'fine balance' between climatic and seasonal patterns, the status of soil fertility and microbial integrity, and native/endemic vegetation. Given these circumstances, there arguably may be only limited opportunities for ecological restoration (*sensu stricto*) following mining in Canada's North.

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[1] Typically reinstatement of conditions having the equivalent structure and function to the pre-disturbance environment (Cooke and Johnson 2002).

[2] For more detailed examples of land rehabilitation, reclamation and/or restoration following mining: cf. Gardner and Bell (2007) regarding bauxite mining in Western Australia; cf. Smith and Nichols (2011) regarding heavy mineral sand mining on the coast of eastern Australia; cf. Tischew et al. (2014) regarding lignite mining in Germany; and, cf. Simmons et al. (2008) regarding coal mining in eastern USA.

Against a backdrop of reclaiming mines in Canada's north, we argue that most contemporary forms of mining (especially open-pit strip mining operations) cause permanent rather than temporary changes to natural landscapes and these changes may represent considerable technical and financial obstacles for the establishment a desired ecological outcome. For better or worse, we should expect that altered physical and social circumstances may lead to alternative ecological outcomes. Clearly, relaxed environmental responsibility and/or grossly oversimplified rehabilitation 'success' criteria are unacceptable approaches to this dilemma in the 21st Century (Clewell and Aronson 2013; Perring et al. 2013). Still, a major challenge lies in achieving the highest standards of biological conservation and ecosystem stewardship when ecological outcomes may not be readily predicted, particularly in an era of global environmental change and heightened environmental awareness. Likewise, how do we prioritize ecological outcomes under these conditions?

2. Defining (new) challenges for mining and land reclamation in the Yukon

Northern Canada holds significant mineral deposits (e.g., copper, gold, lead, molybdenum, silver and zinc) which have led to major hard rock mining projects at Faro Mine, the Keno-Elsa Silver Mine, Ketza River Gold Mine, Mount Nansen Gold Mine and the Brewery Creek Gold Mine. A precursor for many of these operations involved the stakeholders' agreement to design and implement reclamation practices to return affected lands to a reasonable degree of ecological fidelity. These values are summarized (Table 2) in reclamation and mine closure objectives (Yukon Gov't 2013) and focus on five major attributes of the post-mining environments:

- Physical stability (including stability, health and safety),
- Ecological conditions and environmental sustainability,
- Final land-uses and aesthetics, and
- Long-term certainty, socio-economic expectations and financial sustainability.

Indeed, explicitly defining (and negotiating) end-land-use criteria and environmental boundaries for post-mining landscapes provides a clear starting point for setting ecological targets for timely mine closure and lease relinquishment. Realistically, this approach provides a template for identifying desirable ecological attributes that (under optimal biological and socio-economic circumstances) that may inform adaptive management practices and (hopefully) continual improvement of post-mining land stewardship. However, most contemporary forms of mining (especially open-pit strip mining operations) cause permanent rather than temporary changes to natural landscapes and these changes may represent considerable technical and financial obstacles for the establishment or re-instatement of a desired ecological outcome. In each of the cases mentioned above, the size and scale of operations has typically resulted in considerable disturbance to the natural landscape and possible significant alteration of essential landform components – not to mention of the production of many non-natural landscape attributes such as dispersive and possibly even toxic waste-rock and tailings materials. Whereas expectations for mine closure are generally based on the assumption that any desired ecosystem can be established (or re-instated) on the reconstructed landscape, the reality is that characteristics of the post-disturbance environment (including landform hierarchies, physical attributes and biotic composition; Table 2) often bear little to no resemblance to the pre-disturbance environment and are not easily or directly amenable to plant growth – let alone early successional patterns, soil evolution and/or biogeochemical cycling. Here, it should be acknowledged that the number of abandoned, orphaned and/or highly degraded mine sites still far exceeds the number of successfully restored sites (Unger et al. 2012), and the numerous reports of unacceptable changes to environments resulting from mining activities do not enhance the reputation of reclamation, rehabilitation or restoration practice (Worrall et al. 2009).

2.1 Recognizing novelty and novel ecosystems

Specific to the Yukon, many mining developments infringe on boreal or taiga cordillera ecotypes that reflect a 'fine balance' between climatic and seasonal patterns, the status of soil fertility and microbial integrity, and native/endemic vegetation (Price et al. 2013). In an era of climate change (Harris et al., 2006) – in which it is anticipated that changing moisture patterns could alter 'natural' distribution patterns in the development of northern Boreal ecosystems – reliably determining whether long-term ecological trajectories are developing toward "natural" analogues can be challenging. Where sites may require additional management inputs, deriving intervention approaches based on these trajectories can be equally ambiguous and possibly lead to protracted costs of reclamation (Jackson and Hobbs, 2009). Traditional forms of land management that target idealised post-disturbance landscapes based on historical or pre-disturbance ecological criteria (as stated in Table 1) may not always be appropriate for mine sites due to the significant and possibly irreversible differences between the pre- and post-mining environments (Chapin et al., 2010; Doley et al., 2012; Doley and Audet, 2013; 2015). Yet, regulators frequently require that the post-disturbance mining environment be returned and bear close semblance to its pre-disturbance level of composition, structure and functionality. This requirement has sometimes resulted in disjunction between the social and biological expectations for mine sites and the limitation(s) of ecosystem recovery (Worall et al. 2009; Soltanmohammadi et al. 2010; Van Kooten 2011; Burton et al. 2012; Glenn et al. 2014; Hodge 2014). A central question for the sustainable management of legacy mine sites is: "Can today's land reclamation approaches account for future ecological issues and anticipate future environmental management challenges?"

Traditionally, restoration practitioners have targeted the reinstatement of pre-existing (or historical) ecosystems (Hobbs and Cramer 2008). Given the rise of no-analogue environments and continued environmental change worldwide (Harris et al., 2006; Jackson and Hobbs, 2009; Hobbs et al., 2009), an increasing body of literature suggests that many landscapes now contain new and possibly even irreversibly different assemblies of abiotic and biotic system components (Perring et al., 2013) – so called hybrid and novel ecosystems (Hobbs et al., 2006; 2009; 2013). If the post-disturbance environmental conditions bear little resemblance to the pre-disturbance ones, it stands to reason that achieving the return of a sufficient number of landscape components to their pre-disturbance level of ecological integrity may not be economically viable or even ecologically appropriate (Perring et al., 2014). Therefore, it is becoming widely acknowledged that various factors may preclude restoring ecosystems to their pre-disturbance conditions, especially mine sites. Representing a major step forward in the depiction of ecosystem recovery, the definitions of natural vs. novel ecosystems are based on the principle of ecosystem state and transition and the likelihood that disturbance factors can cause (ir)reversible changes to various attributes of the natural landscape. Based on alternative stable-states theory and state-and-transition modelling (cf. Grant 2006; Hobbs and Suding 2009), Hobbs et al. (2013) proposed that novel ecosystems are an outcome of irreversible transfer across abiotic and (or) biotic thresholds. While this may not be the case universally, it is common that the size and severity of mining disturbances (or similar) result in the crossing of abiotic thresholds and that this necessarily involves the crossing of biotic thresholds. And so, both obvious and subtle changes to nutrient and hydrological cycles, landform assemblages and, ultimately, geology and climate typically represent insurmountable barriers to the re-instatement of historical systems. In short, the degree to which disturbances cause ir/reversible changes to ecosystems provides direct insight into the likelihood of rehabilitation efforts either achieving near/natural restoration versus developing hybrid systems (i.e. slightly different in form and function, yet sharing many attributes with the historical system) or even novel systems (i.e. new combinations of physical and biological attributes as a result of novel conditions within the post-disturbance environment). This natural/novel ecosystems paradigm (pioneered by Hobbs et al. 2006) and associated terminology are valuable for depicting the developmental pathways of a range of post-disturbance ecosystems and the management inputs required to re-instate (if practicable) the historical and/or pre-disturbance system (Figure 1).

2.2 Consequences for mining

Rather than criticizing existing practices, we suggest it is preferable to consider the attributes of mine sites that must be managed in order to achieve acceptable ecological restoration. With due deference to empirical evidence, we consider that alternative ecosystems can provide safe, stable and manageable environments with acceptable ecological functions (Perring et al. 2013) that ultimately contribute to the delivery of ecological stewardship and biological conservation benefits (Bullock et al. 2011; Chapin et al. 2010). Yet, the question remains as to how the most responsible, effective and economical outcome may be achieved for the restoration of an extensively disturbed landscape without compromising social or environmental standards. As a starting point for discussion of improved mine stewardship – especially highly degraded sites – Doley and Audet (2013, 2014) suggested moving away from strict adoption of ecological reference sites and applying the natural-novel ecosystem paradigm in order to identify limitations to ecological recovery and obstacles to achievement of a given ecological outcome. However, this conceptual approach requires clear descriptions of the necessary conditions for restoration, along with a willingness to consider alternative ecological trajectories as valued outcomes for the post-disturbance environment. While this reality may appear problematic to the mining industry and its ambition of social and environmental responsibility, we believe that it matters less 'what we call ecosystems' (whether natural or novel) in favour of attempting to achieve the highest standards of biological conservation and ecosystem stewardship in light of circumstance; this, even though ecological outcomes may not always be readily predicted or accounted for during mining's earliest planning stages.

Within a novel ecosystem, it is possible for either biotic or abiotic conditions to resemble those of a historical ecosystem, but restoration is not achieved unless both abiotic and biotic conditions are judged to be sufficiently similar to those of a historical ecosystem. In other words, the novel ecosystem may have similar landscape functions (physical stability, water yield and nutrient balance), but not meet the pre-disturbance criteria of habitat structure or composition due to the persistence of non-native species, novel landscape components, and/or different proportions and combinations of species. In order to guide activities on intensively managed lands, the goals of restoration or rehabilitation need to be clarified and, where possible, quantified; especially the feasibility of attaining a particular restoration or rehabilitation goal in light of the integrity of both biotic and abiotic system components (Grant 2006: Choi 2007; Bullock et al. 2011). In spite of the close relationships between the physical and biotic components of stable landscapes, many mine closure criteria have been expressed in very general terms relating primarily to desired ecological endpoints, and not, e.g., the geologic, climatic, and biological conditions that underpin their form and function. Often, these criteria are inconsistent with the realities and barriers identified even among more successful rehabilitation scenarios (Lindenmayer and Hobbs 2007). Evidently, even within a conceptual realm, the delineation of potential rehabilitation pathways for mine sites would be helpful for establishing why some disturbed mine sites can be returned to their historical status whereas others cannot.

3. Considerations for future land reclamation practices

Land reclamation requires thoughtful assessment of both the pre- and post-disturbance environments (Clewell and Aronson, 2006). This should be followed by careful improvement of key landscape components (such as those listed in Table 2) being mindful of the successional development of recovering ecosystems (Grant 2006, 2009). In the context of large-scale mined land reclamation, greater management resources tend to be allocated toward heavy earthworks for reconstruction of stable landforms and hydrological characteristics to provide the essential structural and functional components of the desired ecosystem. Where climate, geology, and landform reconstruction are not major obstacles to rehabilitation[3], self-sustaining post-mining ecosystems can be achieved with foremost attention to the function and stability of soils. However, due to the size and severity of mining disturbances, post-mining landscapes often contain significantly altered landforms and soils along with non-natural landscape attributes (e.g., waste heaps and tailings impoundments). Consequently, even carefully managed post-mining landscapes may bear little physicochemical and biological similarity to the pre-disturbance environment (Koch and Hobbs, 2007). These disparities may result in different ecological determinants influencing the range of ecosystems that may be established at a given site, which leads to the question of whether the targets dictated by the requirements for ecological stewardship are attainable or even desirable.

Acknowledgment of novel ecosystems in the mining sector can appear problematic since it may imply a permanent loss of historic ecological fidelity when establishing land reclamation goals. Then again, reclamation of highly disturbed post-mining landscapes may not provide realistic opportunities for the redevelopment of "historical" ecological processes and recovery. In fact, the post-mining ecosystems may be quite different from those that occupied the site prior to disturbance, and they may be difficult to anticipate at the planning stage of a mining operation due to the size, complexity, and severity of disturbance and the implications of changing environmental conditions. That does not mean that the ecosystem services provided by these new landscapes are neither valuable nor desirable. There are redeemable attributes to existing land reclamation approaches, so long as policy and regulatory frameworks afford them the flexibility to adjust ecological targets and allocate necessary management resources, should they be required. This underpins the importance of careful planning at the earliest stages of land reclamation, and the necessity to accommodate a capacity to adjust goals according to changing conditions and best practices. Still, the natural-novel ecosystems paradigm most recently proposed by Hobbs et al. (2013) provides a more realistic depiction of the barriers to ecological restoration (including all associated management inputs) necessary for achieving a given environmental target in light of various biological obstacles and socio-economic boundaries (Perring et al., 2013; 2014). Notably, within a hybrid or novel ecosystem, it is possible to have abiotic and biotic conditions that are functionally similar to those found

[3] E.g., referring to environments having a critical starting point with predictable climate patterning, intact geology, and landscape attributes similar to those of the pre-disturbance conditions (Cooke and Johnson, 2002; Gardner and Bell, 2007; Holl, 2002; Smith and Nichols, 2011; Tibbet, 2012; Zipper et al., 2011).

within the broader regional ecosystem, and these ecosystems may represent the best that can be derived following certain industrial disturbances.

Of course, the designation of acceptable hybrid and novel ecosystems should not be used by developers, regulators or policy makers to compromise standards of ecological integrity or conservation. Yet, existing policies and regulations need to account for the fact that many industrial activities cause irreversible changes to landscapes leading to novel ecosystems (Doley and Audet, 2013; 2015). Pragmatically, we can apply our growing ecological understanding of natural versus novel ecosystems for the purposes of adaptive management of mine sites without necessarily needing new approaches or investigative frameworks. A possible advancement for setting more appropriate land reclamation targets would be to move away from establishing reclamation criteria based entirely on conditions of the pre-disturbance environment. Instead, reclamation targets could be established based on current and/or anticipated conditions of the post-disturbance environment. Meanwhile, management regimes should be granted the flexibility to adapt and/or modify their approaches based on ongoing trajectories to determine the range of ecosystems and potential interventions that are optimally supported by these conditions. Ideally, the latter approach would lead to reclaimed ecosystems that provide the greatest ecological resilience under both current and future climatic conditions and other changing environmental drivers, no matter whether these ecosystems are ultimately deemed natural, hybrid, or novel.

4. Acknowledgment

This study is based (in part) on theoretical research into land restoration policy and mine site stewardship by Doley et al. (2012), Doley and Audet (2013, 2015, 2016/In press), and Perring et al. (2013, 2014). Please refer to these studies for further details.

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Table 1 Fundamental Mine Reclamation and Closure Objectives
From: Reclamation and Closure Planning for Hard Rock Mining Projects (Yukon Gov't 2013)

	Value	Reclamation & Closure Objectives
1.	Physical & Stability, Health & Safety	• All mine-related structures, facilities and processes should are physically stable and performing in accordance with designs. • Release of contaminants from mine-related waste materials occurs at rates that do not cause unacceptable exposure in the receiving environment. • Reclamation and closure should eliminate or minimize existing hazards and adverse effects to the health and safety of the public, workers and area wildlife
2.	Ecological Conditions & Sustainability	• Reclamation and closure activities should protect the aquatic, terrestrial and atmospheric environments from mine-related degradation where: o Degraded environments should be restored to (agreed-upon) land-use objectives o Restoration should result in self-sustaining biological communities.
3.	Land-Use & Aesthetics	• Restoration should provide conditions that: o Enable and optimize productive long-term use of land o Are typical of surrounding areas or provide for other land-uses that meet community expectations o Provide site access that is consistent with community land-use expectations o Are visually acceptable
4.	Socio-Economic Expectations	• Reclamation and closure implementation should: o Avoid adverse socio-economic effects on local communities o Meet community and regulatory expectations
5.	Long-term Certainty & Financial Considerations	• After reclamation activities are complete, minimize the need: o For long-term operations, maintenance and monitoring o For outstanding liability and risk

Table 2 Hierarchies of abiotic and biotic landscape complexity.
From: Doley & Audet (2013), based on Tongway & Ludwig (2011)

Factor		Attribute	Physical Property	
Abiotic	Geology*	Consolidation		
		Origin		
		Mineralogy		
		Texture		
	Landscape	Form	Landform Class	
			Landform Pattern	
			Landform Element	
			Quantitative Attributes	Relief
				Slope
				Texture
		Function	Surface	Erosion
				Deposition
			Biogeochemical Profile	pH
				EC
				Nutrient Status
				Water Status
Biotic	Vegetation	Structure	Height	
			Cover	
			Biomass	
		Composition	Species Richness	
			Diversity	
			Structural Class	
		Integrity		
	Fauna**	Abundance		
		Diversity		

*Including the geology and biogeochemistry of the parent material.
**Including both above- and belowground biota.

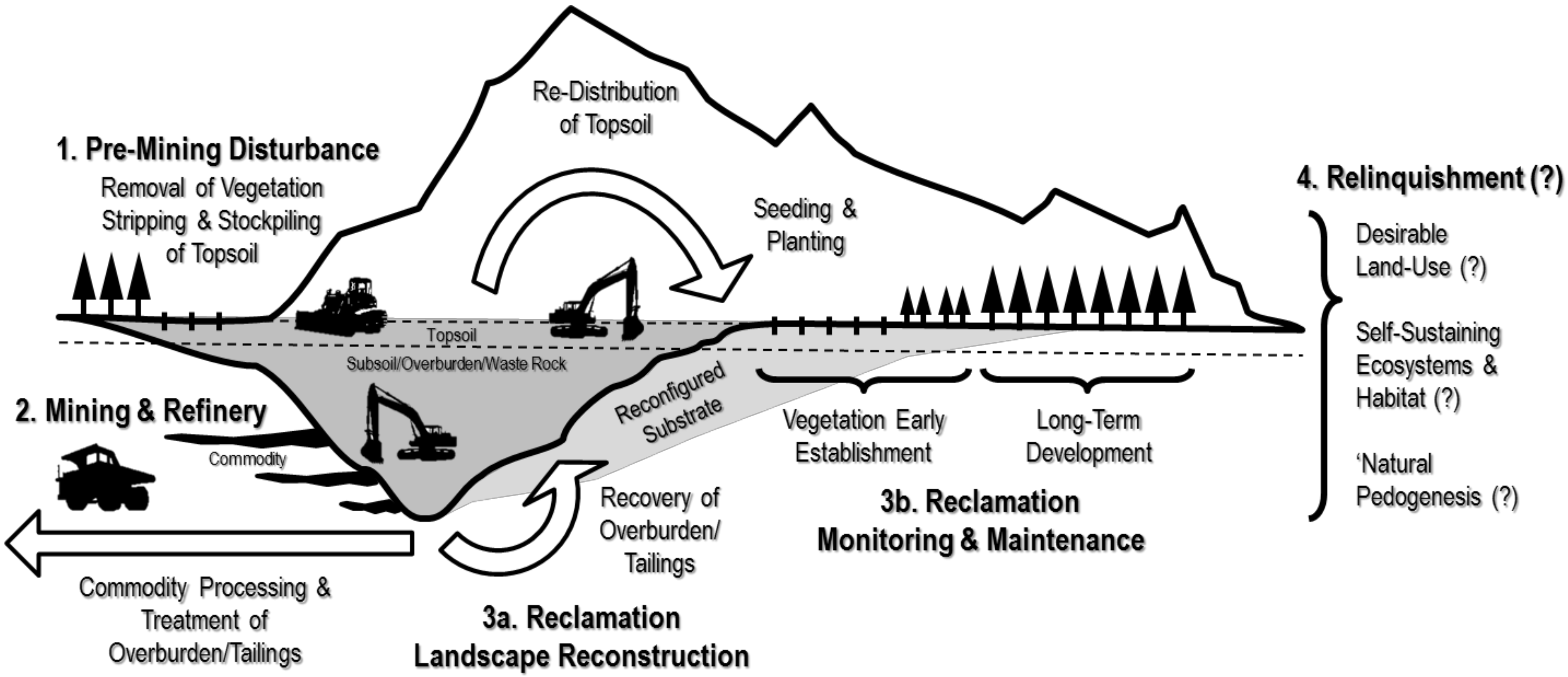

Figure 1 Summary of contemporary life-of-mine procedures associated with open-pit and/or strip mining; from Doley and Audet (2015), based on Audet et al. (2015). During the pre-mining phase (1), vegetation is removed and cover soils (~20–50 cm containing native plant propagules and indigenous soil microbial) are stripped for later use in the landscape reconstruction phase of reclamation. After mining (2), subsoils consisting of recovered overburden and tailings materials are configured to reconstruct the post-disturbance landform and facilitate revegetation (3a). During the monitoring and maintenance phase of reclamation (3b), site maintenance may range from soil amendment, vegetation biocontrol and/or management of habitat to facilitate desirable land-uses and self-sustaining ecological processes (4).

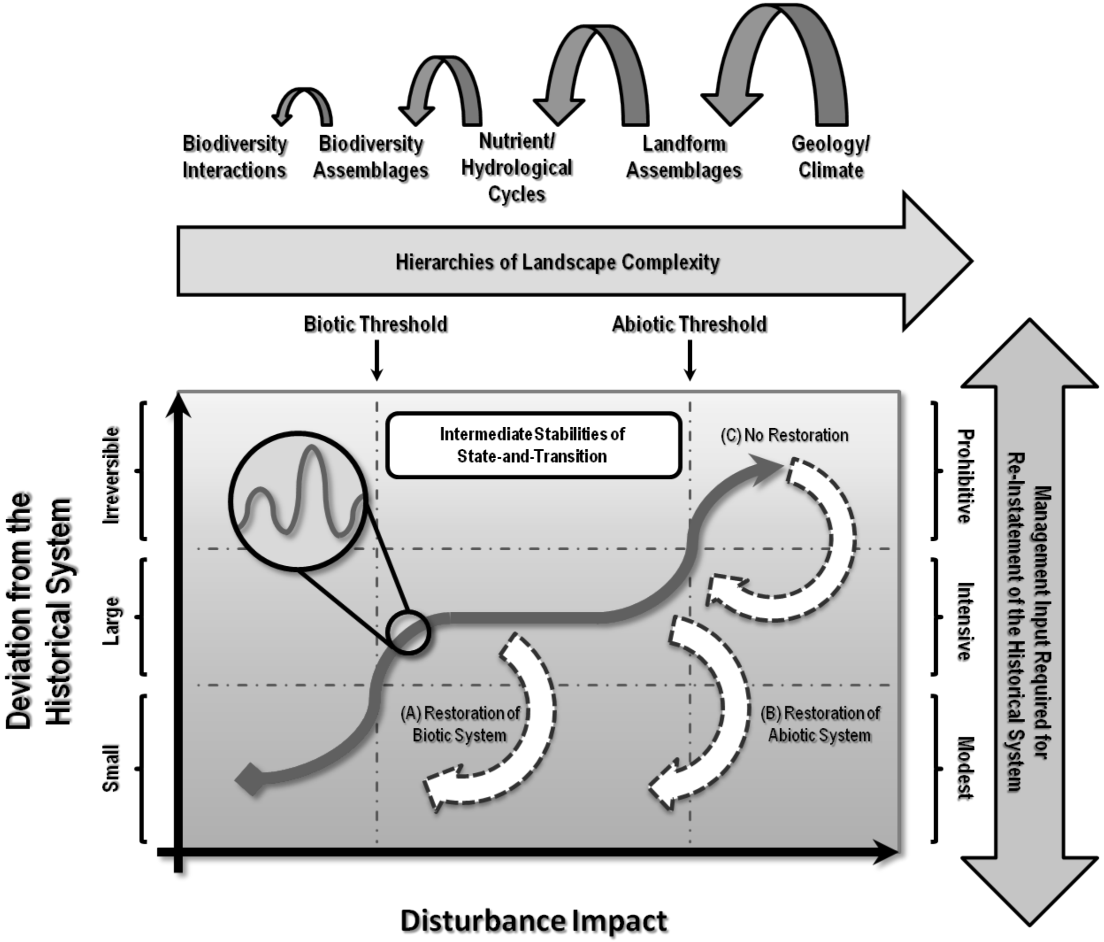

Figure 2 Intermediate stabilities of state-and-transition for ecosystems subjected to increasing size and severity of disturbance impact; from Doley and Audet (2013, 2015). Deviation from the historical system increases (from small to large to irreversible) due to crossing of increasing hierarchies of landscape complexity resulting in commensurate increases in management input required for re-instatement (from modest to intensive to prohibitive) (adapted from Jackson and Hobbs 2009). Ir/reversibility of biotic and abiotic thresholds determines the likelihood of (a) restoration of the biotic system, (b) restoration of the abiotic system, or (c) no restoration.