Factors Affecting Ecological Resilience of Reclaimed Oil Sands Uplands

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REPORT SUMMARY

This literature review provides an understanding of ecological resilience as a concept to promote successful land reclamation in Alberta's mineable oil sands region by exploring four key issues:

Defining ecological resilience for boreal forest ecosystems,
and assessing whether this definition can be applied to reclaimed oil sands
landscapes or requires modification.

Resilience is an emergent property of ecosystems. It is an outcome of their inherent capacity for self-organization – the interaction between structure and process that leads to system development. Resilience constitutes the relative susceptibility of a given community to switches into alternative states as a result of the interaction between autogenic (competition, for example), allogenic (fire, wind, harvesting, and climate, as examples) and biogenic (insect epidemics, diseases, as examples) processes.

In principle, the concept of resilience could have considerable utility in designing reclamation systems for the oil sands. One application of the concept, the length of time that a system takes to return to equilibrium following perturbation (engineering resilience), is to use rates and patterns of development from the natural forested ecosystems in the region as a benchmark. Hence, the resilience of reclaimed systems would be evaluated with respect to the extent to which these patterns and rates are congruent. Several metrics in the current version of the *Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region* (indicator species and similarity indices, for example) suggest the utility of this approach has been recognized, though not necessarily within the context of resilience. Ecological resilience, the amount of perturbation a system can withstand before it moves into a different state, is pertinent because it constitutes the conceptual basis for designing practices that confer resilience in reclaimed ecosystems. Examples of these practices include minimizing chronic stress (acid deposition, for example), ensuring the rooting zone is conducive to plant establishment and productivity, and a functionally diverse community (both and above and belowground).

Resilience in natural and reclaimed ecosystems are mirror images. Applying the concept in natural systems is to pose the question, "how much can self-organizing capabilities be *perturbed* and still achieve desired outcomes"? In the case of reclamation the question becomes, "how much of the self-organization capabilities of a system must be *created* to achieve desired outcomes?"

Describing a range of ecological and anthropogenic disturbances
a reclaimed oil sands upland site might experience

In terms of the ecological disturbances a reclaimed oil sands upland site might experience, these are fire, insects and pathogens, drought, wind, site dominance (invasion) by non-local species (native and non-native), and climate variability. Anthropogenic disturbances include erosion, issues associated with soil structure and related physical properties, salinity and sodicity, contaminants (bitumen, naphthenic acids), excessively high and low soil pH, and climate change.

Describing physical, chemical and biological characteristics of reclaimed upland sites that would confer resilience to the range of ecological and anthropogenic disturbances identified above

Three approaches are described for addressing the physical, chemical and biological characteristics (structure, composition, function) of reclaimed upland sites that would confer resilience to the range of ecological and anthropogenic disturbances identified above. From the general to the specific, these approaches focus on (a) general ecosystem attributes, (b) on functions that need to be maintained, and (c) attributes that confer resilience against specific perturbations or stressors.

Describing reclamation and management practices necessary to generate ecological resilience in oil sands upland landscapes

Managing for resilience is to implement reclamation practices and procedures that maximize the probability a given desired state will emerge or persist over the time period of interest. The underpinning of resilient ecosystems is a rooting zone conducive to plant establishment and productivity, with a functionally diverse community (both above and belowground) to maximize the potential that development will be maintained along desired trajectories. To create resilient ecosystems, management must focus on both mitigative and adaptive strategies. Mitigative actions confer resilience by eliminating or reducing exposure to chronic stresses (nitrogen and sulfur deposition or salt intrusion, for example). The adaptive approach focuses on traits that allow plant species to tolerate chronic stress or that predispose them to changes in the disturbance regime (fire or climate change, for example).

To measure resilience one needs to define the time scale over which a system is resilient, with the choice of scale dependent of the issue under investigation. In the case of reclamation, relevant scales could vary from several decades (the time period over which a reclamation certificate might be awarded) to a century, or more. In principle, resilience could be predicted from models that incorporate the critical processes driving ecosystem productivity and community development but in practice, this is likely not practical due to data limitations. Nevertheless, models can play a useful role in identifying indicators that may signal ecosystem resilience and vulnerability.

The review identifies the top three characteristics that confer ecological resilience in oil sand upland landscapes. These are

1. Species diversity, with a particular emphasis on functional diversity
2. A quality rooting zone
3. Minimize nitrogen and sulfur deposition.

Designing and assessing resilience in reclaimed oil sands ecosystems will likely require a combination of empirical measures informed by model outputs. Models can be used to project the long-term consequences of a given reclamation prescription while specifying which particular ecosystem attributes are relevant to a monitoring program and the time frame when the requirements for a reclamation certificate could be met. In that respect, model outputs, ecological measures, and checklists which identify management activities, decisions and interventions should be developed collectively, and comprise a decision support system that can address the question ‘Does this reclaimed upland site possess or is capable of developing, characteristics of a resilient ecosystem?’

ACKNOWLEDGEMENTS

The Oil Sands Research and Information Network (OSRIN), School of Energy and the Environment (SEE), University of Alberta provided funding for this project. Attendees of the *Resiliency of Reclaimed Boreal Forest Landscapes*[1] workshop, held at the University of Alberta, January 22, 2013, provided valuable insights that contributed to the ideas presented herein. I thank Caroline Bampfylde, Chi Chen, Gillian Donald, Chris Powter, and Brett Purdy for their comments on the report. Any errors and omissions are fully the responsibility of the author.

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[1] Pyper, M.P., C.B. Powter and T. Vinge, 2013. *Summary of Resiliency of Reclaimed Boreal Forest Landscapes Seminar*. OSRIN Report No. TR-30. 131 pp. http://hdl.handle.net/10402/era.30360

1 INTRODUCTION

The reclamation goal for oil sands mines, as specified in the environmental operating approvals issued under the *Environmental Protection and Enhancement Act* is to *reclaim the land so that the reclaimed soils and landforms are capable of supporting self-sustaining, locally common boreal forest ecosystems, regardless of the end land use*[2].

In the field of ecology, resilience was first defined by Holling (1973) and can be broadly described as the capacity of an ecosystem to resist and recover from a perturbation or disturbance[3]. Resilience is one potential measure of the goal of a *self-sustaining* ecosystem and is being considered for inclusion in the Cumulative Environmental Management Association's Criteria and Indicators Framework for assessing reclamation success (Poscente and Charette 2012). For reclaimed oil sands uplands to be considered *self-sustaining*, they should respond to natural and anthropogenic disturbance in a manner similar to how an analogous undisturbed landscape might respond to the same disturbance.

Reclaimed oil sands mine landscapes will have a diversity of slopes and aspects, substrates (e.g., overburden, tailings sand, soft tailings), soil depths and mixes, vegetation (planted and volunteer), and potential land uses (e.g., commercial forestry, recreation, wildlife habitat, traditional use), each of which may impact the ability of the system as a whole to respond to disturbance[4].

1.1 Specific Project Objectives

This literature review provides an understanding of ecological resilience as a concept to promote successful land reclamation in Alberta's mineable oil sands region by exploring four key issues:

- defining ecological resilience for boreal forest ecosystems, and determining whether this definition can be applied to reclaimed oil sands upland landscapes[5] or requires modification;
- describing a range of ecological and anthropogenic disturbances a reclaimed oil sands upland site might reasonably be expected to experience;
- describing physical, chemical and biological characteristics (structure, composition, function) of reclaimed upland sites that would confer resilience to the range of ecological and anthropogenic disturbances identified above; and

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[2] See, for example, s. 6.2.1 in the Total E&P Canada Ltd. Joslyn North Oil Sands Processing Plant and associated Mines approval – http://envext02.env.gov.ab.ca/pdf/00228044-00-00.pdf

[3] See section 7 for definitions of terms and acronyms used in this report.

[4] See also Pyper, M.P., C.B. Powter and T. Vinge, 2013. *Summary of Resiliency of Reclaimed Boreal Forest Landscapes Seminar*. OSRIN Report No. TR-30. 131 pp. http://hdl.handle.net/10402/era.30360

[5] This report focuses on reclaimed upland landscapes. There is a need to explore similar questions for reclaimed wetland landscapes.

- describing reclamation and management practices necessary to generate ecological resilience in oil sand upland landscapes.

The review also:

- identifies the top three characteristics that confer ecological resilience in oil sand upland landscapes; and
- provides relevant examples where ecological resilience in other degraded landscapes was tested or evaluated.

1.2 Basic Approach

Typically, reviews of this type are based on one of two approaches. An inductive approach seeks to identify patterns and commonalities relevant to the review topic after summarizing the information contained within a large numbers of documents; in essence, commonalities (hypotheses and principles) ‘emerge’ from the data. The second approach is to employ a deductive method, whereby the review begins with a summary of current organizational concepts and ideas (hypotheses) that are then used to ‘filter’ information about each hypothesis as either supportive, or not. It is the latter that will constitute the basis for our review because:

1. The reclamation literature has grown substantially in recent years as mine operators strive to satisfy increasingly stringent regulations concerning mitigative obligations. Hence, the inductive approach is an impractical means of satisfying the review objectives.
2. Hypotheses are the means of formalizing our understanding of how nature operates and how we interact with the natural world (from a management perspective). In this case, evaluating information for its consistency with a given hypothesis is an efficient means of ‘testing’ how well we understand resilience and devising effective methods for its application in oil sands reclamation practices.

Resilience is an emergent property of ecosystems that is an outcome of their inherent capacity for self-organization. *Self-organization* refers to the interaction between structure and process that leads to system development. As such, resilience is a challenging paradigm to interpret and implement because these systems cannot easily be ‘deconstructed’ with the aim of studying the behavior of each (simplified) part in isolation; in systems that display emergence, the whole is by definition something else than the sum of its parts (Solé and Bascompte 2006)[6]. Nevertheless, a number of core principles have been derived and though their application has its challenges, the

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[6] That the properties of individual units cannot always explain the whole has been long recognized. Life itself is an example of an emergent property. For instance, a single-celled bacterium is alive, but if you separate the macromolecules that combined to create the bacterium, these units are not alive. Population and community dynamics cannot be predicted simply from knowledge of their constituent members (either individuals or species). Emergence and self-organization highlight the limitation of reductionism in ecology (and by extension, reclamation) in spite of the fact that the latter approach is the *de facto* method.

concept of resilience has emerged as an important and useful paradigm in ecological management.

The review will be comprised of four sections such that a given section satisfies one of the four principle activities defined in section 1.1, and in sequence they build the knowledge base necessary to satisfy all of the required objectives. Section 2 will present the theoretical underpinnings of ecological resilience since the concept must be clearly understood and translated to practitioners if it is to be useful and meaningfully applied. Section 3 constitutes a review of ecological and anthropogenic disturbance applicable to the mineable oil sands region. Factors that confer stability/resilience are considered in section 4, and section 5 describes reclamation and management practices necessary to generate ecological resilience in oil sand upland landscapes, and how resilience might be measured. Finally, the review will also:

- identify the top three characteristics that confer ecological resilience in oil sand upland landscapes (section 6); and
- provide relevant examples throughout the review where ecological resilience in other degraded landscapes was tested or evaluated.

2 DEFINING ECOLOGICAL RESILIENCE

2.1 The Stability-Resilience Dichotomy

The debate about stability in ecological theory is marked by a frightful confusion of terms and concepts

Grimm et al. (1992) made this statement two decades ago, and little has changed in the interim; it is also equally applicable when the term ‘resilience’ is substituted for ‘stability’. Resilience has been defined in the ecological literature in two different ways, each reflecting different aspects of stability (Gunderson 2000, Kimmins et al. 2010). In one case, stability constitutes a pre-condition of resilience, whereby resilience is the length of time that a system takes to return to equilibrium (stability) following perturbation (i.e., disturbance; Pimm 1984). Populations of annual plants are therefore more resilient than trees, for example. Another term used for this is engineering resilience (Holling 1996). Holling (1973) introduced a variation on this theme with the term ‘ecological’ resilience, the amount of perturbation a system can withstand before it moves into a different basin of attraction, stability domain, or state (see below). These latter terms are used interchangeably; they refer to the dominant assemblage of species forming an ecosystem at a point in space and time, the functional roles those species play, and their characteristic vegetation structures, including height, canopy layers, stem density, etc. (modified from Thompson et al. 2009).

Kimmins et al. (2010) consider elastic and inertial stability as equivalent to engineering and ecological resilience, respectively. They also argue that inertial stability may be more applicable to populations rather than ecosystems because disturbance is often a key component of succession, a population process; in the case of ecosystems, elastic stability thus appears to be a more applicable idea. Before further developing these concepts within the context of reclamation, it is useful to remember that change over time is ubiquitous in complex systems. Individuals, for example, display striking changes in their physical appearance over time, population numbers can vary widely on a seasonal or annual basis, while the process of succession generates changes in the dominant species within plant communities over decades, or longer.

In the case of a forest community, there are three dominant processes that drive change, autogenic, allogenic, and biogenic (see Figure 1). Resilience then constitutes the relative susceptibility of a given community to switch into an alternative state as a result of these processes. In this respect, Drever et al. (2006) suggest that changes in a forest as it ages are not necessarily a change in state but may reflect compositional and structural change internal to the system (see Figure 1). Thompson et al. (2009) also point out, however, that a forest once dominated by a certain suite of species but that changed as a result of new environmental conditions or human interference, has switched ecosystem states. In their example, if a harvested boreal spruce-pine-dominated forest regenerates to a mixedwood (i.e., it now contains a deciduous component), that system has switched states because the dominant taxonomic composition of the canopy trees has changed, along with processes such as rates of growth and types of pollination.

A convenient metaphor often used to illustrate the concept of resilience is that of a ‘marble-in-a-cup’ (Figure 2; see, for example, Gunderson 2000, Gunderson and Holling 2002). A system is in equilibrium when the marble sits at the bottom of a cup. Disturbance displaces the marble and if the system is sufficiently resilient, the marble will return to the equilibrium position. Exceeding the system’s resilient capabilities pushes the marble to a different equilibrium. Engineering resilience refers to characteristics of the shape of the cup – the slope of the sides dictates the return time of the ball to the bottom of the cup. Ecological resilience is represented by the cup width. The fact the ecological landscape is comprised of potentially more than one cup indicates that there are alternative states that an ecosystem can occupy[7]. Implicit in both of these definitions is the assumption that resilience is a static property of systems. That is, once defined, the shape of the cup remains fixed over time. As Gunderson (2000) points out, however, stability domains are dynamic and variable. An illustration of the relationship of the ‘marble-and-cup’ to patterns of forest community development is provided in Figure 3.

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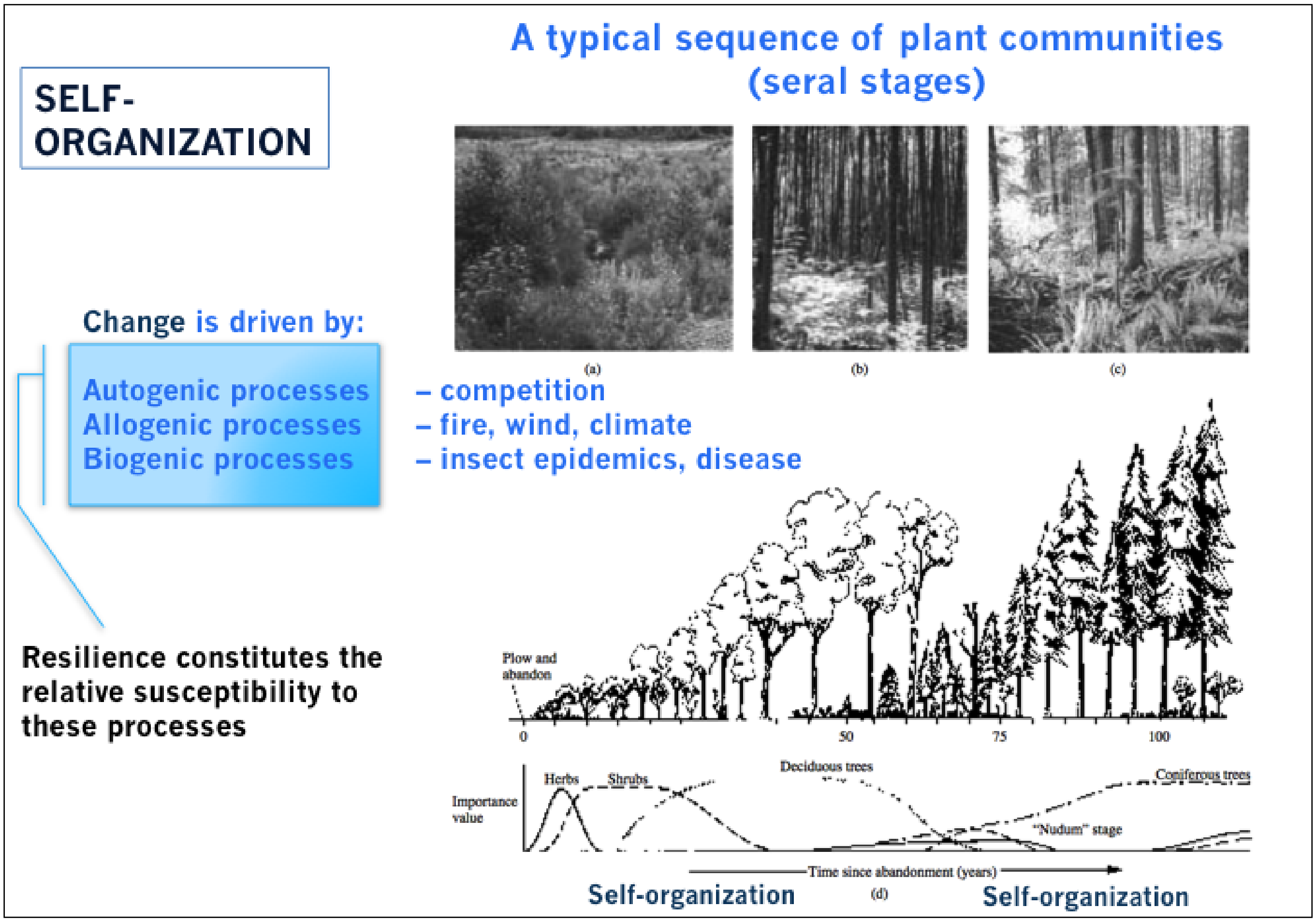
[7] It is useful to note that although the new state may be ecologically stable, stakeholders may not view the new cup (state) as *desirable*. Stakeholder views on desired land uses may be found in:
Jones, R.K. and D. Forrest, 2010. Oil Sands Mining Reclamation Challenge Dialogue – Report and Appendices. OSRIN Report No. TR-4. 258 pp. http://hdl.handle.net/10402/era.19092
Oil Sands Research and Information Network, 2011. Equivalent Land Capability Workshop Summary Notes. OSRIN Report TR-13. 83 pp. http://hdl.handle.net/10402/era.23385



SELF-ORGANIZATION

A typical sequence of plant communities (seral stages)

Change is driven by:

- Autogenic processes – competition
- Allogenic processes – fire, wind, climate
- Biogenic processes – insect epidemics, disease

Resilience constitutes the relative susceptibility to these processes

Self-organization

Self-organization

Figure 1. Successional change as an illustration of the self-organizational capabilities of forest ecosystems as driven by autogenic, allogenic, and biogenic processes.
These three processes destabilize the system by altering its structure and/or the underlying processes that give rise to structure.
Resilience is applicable at several temporal scales – the ability of a given successional stage to maintain itself represents one stable state, as does the extent to which the seral sequence is maintained following a stand-replacing disturbance.
Figure modified from Kimmins (1997).

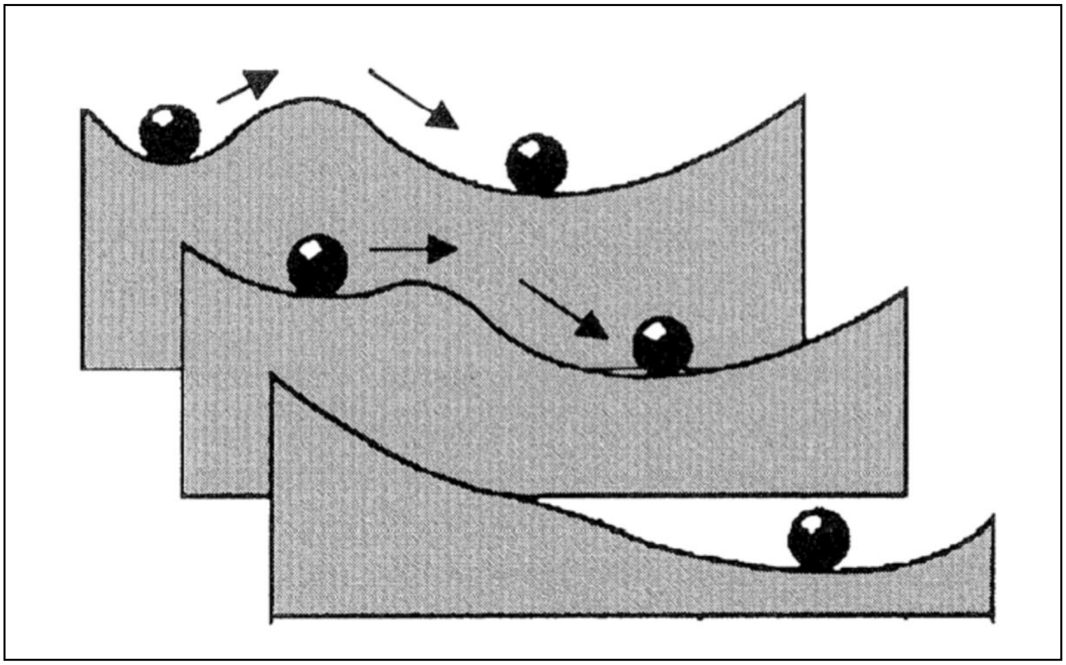


Figure 2. Marble-and-cup heuristic of system stability.
Valleys represent stability domains, marbles are the current state of the system, and arrows are disturbances.
The slope of a given valley constitutes engineering resilience (the steeper the slope the faster the system returns to an equilibrium position at the bottom of a valley); ecological resilience is described by the width of a valley.
A perturbation can push the system from one valley to another. However, chronic changes (in climate or soil, for example) can alter the shape of the stability landscape (as demonstrated by the three different images).
From Gunderson (2000).

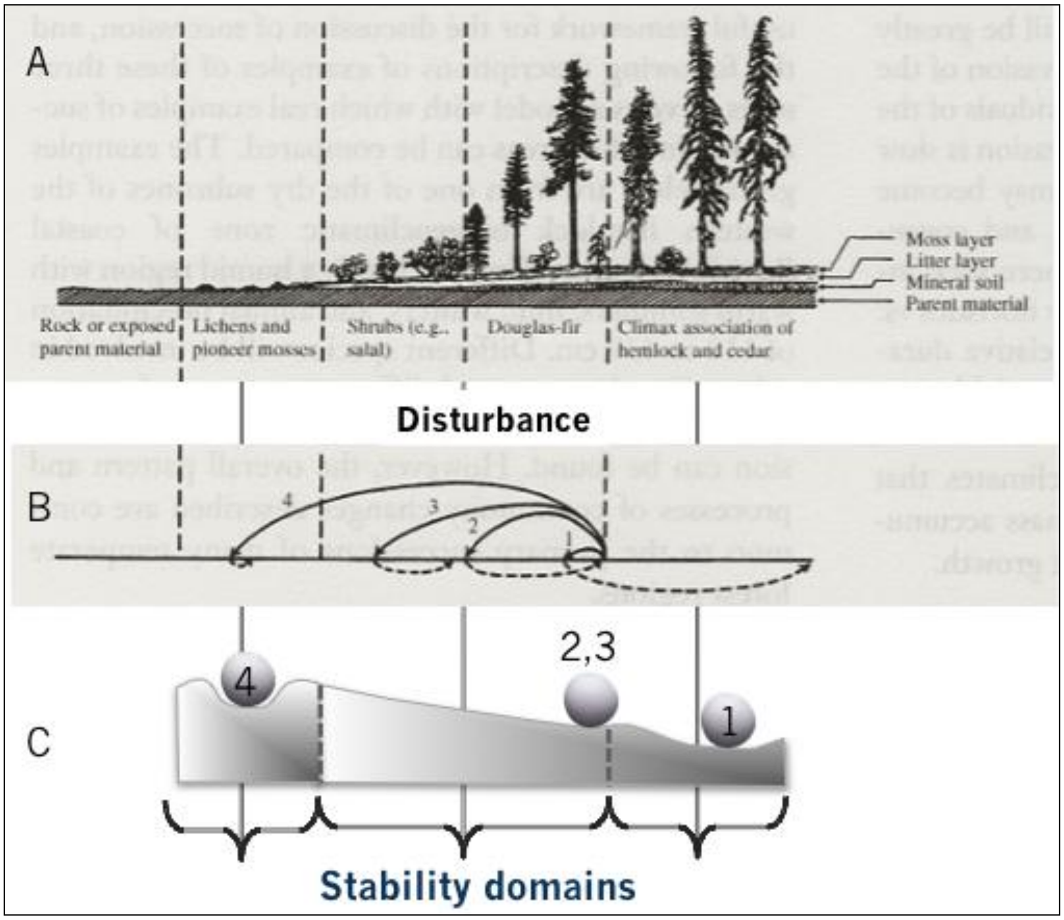


Figure 3. A pattern of forest community development typical of coastal British Columbia.
A. The community begins with a period characterized by lichens and pioneer mosses before conditions have been modified sufficiently to support a shrub community. This is followed by tree cover dominated by Douglas-fir (*Pseudotsuga menziesii*) that transitions to a climax community of hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*).
B. A community can require a relatively minor disturbance event (windthrow, for example) to spur further development (disturbance type 1), or development can be 'reset' by disturbance events (types 2 to 4).
C. In this example, development can reach any one of three equilibria, depending on the disturbance intensity. An insect outbreak or moderate fire (disturbances 2 and 3), for example, means the community will likely reach an equilibrium dominated by Douglas-fir, unless another minor disturbance (type 1) pushes it forward into the hemlock-redcedar stage. A severe disturbance such as wildfire (type 4) can move the system into an entirely different stability domain (i.e., a different valley in Figure 2). In this case, for example, it is assumed that most of the organic material is killed and/or burnt thereby favoring lichens and moss. Note that the diagram gives no indication of the length of time that a given stage is dominant.
Modified from Kimmins (2007).

Recently, the concept of resilience has been broadened to include consideration of ecosystems as complex adaptive systems (CASs). First developed by Levin (1998), a CAS is characterized by patterns at higher levels that emerge from localized interactions and processes acting at lower levels. Macroscopic system properties such as trophic structure (how energy is acquired by the organisms at different levels – producers, consumers, and decomposers – within the ecosystem), diversity-productivity relationships, and patterns of nutrient flux thus emerge from interactions among components, and may feed back to influence the subsequent development of those interactions (Levin 1998). Forests exhibit all of the characteristics of CASs (see Puettmann et al. 2013). Of the four basic properties of a CAS (aggregation, nonlinearity, diversity, and flows), diversity may be the most relevant for oil sands reclamation through the resilience that is conferred to ecosystems by the presence of keystone species, and keystone functional groups (Levin 1998; see below). Resilience can only be properly understood and evaluated, however, by focusing on the interactions among the various components of the system rather than on individual components considered in isolation, the traditional, reductionist approach to ecology (Puettmann et al. 2013).

A review of resilience would not be complete without consideration of the concept of panarchy. Formally developed by Gunderson and Holling (2002), panarchy is the structure in which ecosystems are interlinked in continual adaptive cycles of exploitation, conservation, creative destruction, and reorganization (see also Carpenter et al. 2001). As the adaptive cycle proceeds through these phases, ecological resilience expands and then contracts. A key point is that resilience is a dynamic (versus a static) feature of ecosystem development, which has important implications for how resilience is assessed and evaluated. In natural forests, the mature, late seral (conservation) stage is considered to be less resilient than the previous (exploitative) stage from which it arises. Though this stage appears to be resilient to change, stability is local and narrow (Gunderson 2000). Hence, disturbance (fire, for example) can trigger a catastrophic transformation (creative destruction) leading to reorganization, the next phase. During reorganization, connectedness among community members is low, which can promote novelty in terms of species function. The system can also experience a shift in species composition (this stage is vulnerable to invasion by exotic species, for example) leading to a change in developmental trajectory. The subsequent exploitation phase is the stage at which resilience is highest. Early in this phase, many species exhibit high growth rates and high reproductive output in an effort to monopolize available growing space. Over time, competition and connectedness increase and slow growing, long-lived species predominate until the cycle of renewal begins anew.

Carpenter et al. (2001) point out that as a metaphor, panarchy has considerable utility but the concept does not lend itself easily to testable hypotheses. Perhaps the simplest way to define resilience is the extent to which a community (reclaimed or otherwise) will continue to develop along a trajectory that is likely to generate a desired condition. This idea is developed further below.

2.2 Resilience over Time (Succession) and Space (Shifting Mosaics)

Change over time is one of the five characteristic features of ecosystems (see Kimmins 2007). In the case of forests, stand-replacing disturbances such as fire induce drastic changes in the composition, structure and processes that characterize these ecosystems. Considering the changes in biota, forest floor and some mineral soil horizons associated with both stand dynamics and succession, what does resilience at the stand level actually mean? One approach is to consider resilience as a non-declining pattern of change, which Kimmins (2007) defined as the ecological rotation (within the context of sustainable forest management). The ecological rotation is achieved when three variables are in balance – frequency of disturbance, severity of disturbance, and rates of stand development and ecosystem “recovery” following disturbance. Hence, the structure and functions of ecosystems can be altered drastically through disturbance but resilience ensures that over time (the ecological rotation) these features will be restored to qualitatively similar levels. Drever et al. (2006) express this concept more fully in terms of the panarchy concept developed by Gunderson and Holling (2002).

Landscape level resilience refers to variables such as pattern, scale, patch size frequency, fragmentation and connectivity – terms that relate stand-level properties and the distribution of stands that results from a given disturbance regime. Resilience at the landscape level thus involves a shifting mosaic of stands at different stages of development (Drever et al. 2006), but with each stand exhibiting a pattern of non-declining change (Kimmins et al. 2010). Given a landscape of sufficient size, the shifting mosaic collectively generates a stable overall character (resilience).

2.3 Applying the Definition of Resilience to Reclaimed Ecosystems

2.3.1 *Are the Definitions Appropriate?*

In principle, the concept of resilience could have considerable utility in designing and assessing reclamation systems for the oil sands.

One application of the definition of engineering resilience (see s. 2.1) is to use rates and patterns of development from natural forested ecosystems in the region as a benchmark[8]. Hence, the engineering resilience associated with reclaimed systems would be evaluated with respect to the extent to which these patterns and rates are congruent. Several metrics in the current version of the *Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region* (indicator species, similarity indices; Alberta Environment 2010) suggest the utility of this approach has been recognized, though not necessarily within the context of resilience. Other metrics may also be useful, such as nutrient cycling (DeAngelis 1980) and biomass accumulation (Pimm 1984).

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[8] Other terms used in discussions of oil sands reclamation assessment include *reference site/area*, *reference condition*, and *analogue*.

Ecological resilience (see s. 2.1) is pertinent because it constitutes the conceptual basis for designing practices that confer resilience in reclaimed ecosystems. Resilience in natural and reclaimed ecosystems are mirror images. Applying the concept in natural systems is to pose the question, "how much can self-organizing capabilities be *perturbed* and still achieve desired outcomes"? In the case of reclamation the question becomes, "how much of the self-organization capabilities of a system must be *created* to achieve desired outcomes?" and which is the crux of ecological resilience. This distinction between natural and reclaimed ecosystems is illustrated in Figure 4. Across millennia, natural ecosystems undergo repeated cycles of growth, disturbance and renewal. These cycles are co-dependent in that development within a given cycle is influenced by the historical legacy of the previous cycle (see Figure 4; Drever et al. 2006).

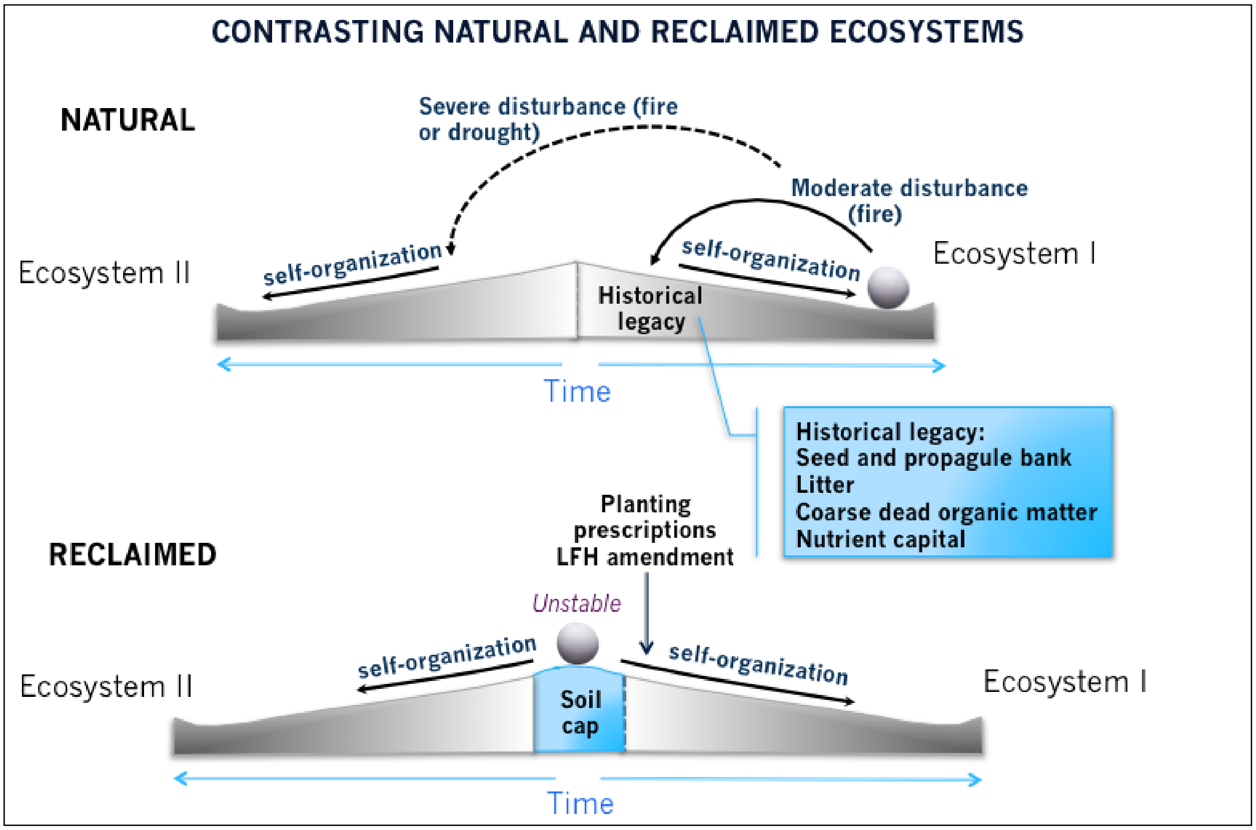

Figure 4. The distinction between natural and reclaimed systems with respect to resilience during the initial stages of stand development.
Natural systems are inherently resilient because they possess a historical legacy that influences subsequent patterns of self-organization. Reclaimed systems have low resilience initially because they lack a true historical legacy (see text for further details).

As Drever et al. (2006) articulate, a forest ‘remembers’ (*sensu* Holling and Gunderson 2002) its pre-disturbance composition and structure by virtue of its biological legacy, mobile links, and support areas. Biological legacies are species, patterns, or structures (such as surviving trees that serve as seed sources, regenerative material like rhizomes, and nutrients) that act as sources of ecosystem recovery (Franklin and MacMahon 2000). Mobile links are “keystone” organisms that move into disturbed habitats to provide essential ecosystem processes, such as pollination and seed dispersal (Lundberg and Moberg 2003). Support areas refer to landscape patches or habitats that maintain viable populations of mobile links (Lundberg and Moberg 2003). Together these interacting parts play a pivotal role in renewal and reorganization of a disturbed system.

In a sense then, the historical legacy is of critical importance because it predisposes the system (i.e., reinforces resilience) towards a defined pattern of self-organization (Gunderson and Holling 2002). This contrasts with historical reclaimed oil sands upland ecosystems, which lack many of the features that define the historical legacy (see Figure 4), because the soil capping material that forms the rooting zone is peat-based. Hence, its biogeochemistry differs from the litter-based organic material in natural ecosystems, and its seed and propagule banks are much reduced. To partly compensate for these differences, current reclamation prescriptions include a revegetation component and when possible, the addition of LFH (forest floor) material. The latter is anticipated to function as a source for propagules representative of natural upland ecosystems and thus aid in regeneration (see Mackenzie and Naeth 2010)[9]. These efforts serve to impart resilience, at least in a narrow sense, because they ‘push’ the reclaimed ecosystem towards a desired stability domain (i.e., an end land-use objective). Nevertheless, it seems likely that a reclaimed community has low resilience during the early reorganization phase (*sensu* Gunderson and Holling 2002) in that even small variations in initial conditions (or perturbations) could generate very different patterns of community development.

2.3.2 *Resilience in Space*

As noted above (s. 2.2) scale is an important consideration when evaluating resilience. Spatial scale has a profound impact on the processes underlying ecosystem recovery. ‘Interior’ processes, for example, dominate large-scale stand-replacing events (of several hundred hectares, and larger), because their edges are small relative to the area contained within the disturbance. Hence, colonization and vegetation re-establishment will occur predominantly from within the disturbance area rather than through on-site dispersal.

Small-scale disturbances can be impacted by a high degree of propagule ingress through wind dispersal. This serves to promote species diversity and, hence, resilience, and is an example of how the role of biological diversity can operate across scales (see Elmqvist et al. 2003). Another feature is that small-scale disturbances possess a relatively large transitional boundary (the ecotone) from the exterior to the interior (Peters et al. 2006). These transitional zones often

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[9] OSRIN will be releasing a literature review in Summer 2013 on the benefits of using LFH-based reclamation materials.

display properties unique from the surrounding areas (Walker et al. 2003) suggesting that they may develop along trajectories with stability domains that are difficult to predict (Peterson 2002).

Natural systems are subject to perturbations that span a broad spatial scale, from the death of individual trees to stand-replacing disturbances like wildfire and insect epidemics (Mountain Pine beetle *Dendroctonus ponderosae*, for example) that cover thousands to millions of hectares. These disturbance events serve to remove living biomass, at least temporarily, and create an opening within an essentially continuous area of forest cover. This contrasts sharply with reclaimed ecosystems. A given oil sands mine footprint constitutes a disturbance of several tens of thousands of hectares in size and with ongoing mining activities, is anticipated to be reclaimed progressively over the life of the mine. Hence, areas reclaimed each year will be relatively small in size (perhaps tens of hectares, or less) and thus will possess essentially no interior condition i.e., their processes will be dominated by edge effects. Furthermore, most reclamation will occur during the latter stages of mine activity and post-mining, which means that many of the initial reclaimed sites will develop in physical isolation from mature forest. This suggests that the rates of ingress typical of small natural disturbances will be significantly impaired. Assuming these sites are successfully reclaimed, however, they could represent important seed sources for the majority of sites that are reclaimed later and as a source of organisms that can move into these new habitats.

Lundberg and Moberg (2003) refer to organisms that actively move in the landscape and connect habitats in space and time as "mobile links." They argue that these constitute essential components in the dynamics of ecosystem development and resilience by promoting buffer capacity and as sources for reorganization after disturbance.

2.3.3 *Resilience and Time*

Elmqvist et al. (2003) suggest that the persistence of ecological function over time (i.e., resilience) depends on the diversity of response by different species within a functional group to changing environmental conditions (see s. 4.2). Typically, managing for resilience is to employ practices that *maintain* diversity at a range of temporal and spatial scales (Drever et al. 2006, Elmqvist et al. 2003). The challenge with oil sands reclamation is to ensure sufficient diversity is *established* so that ecosystem development proceeds along a desired trajectory. This is accomplished initially through planting and with the application of LFH material. As noted above, rates of species ingress may be low, at least in the early stages of reclamation, because relatively little land will have been reclaimed and it may be isolated from natural propagule sources. Ensuring all existing native plant species (not only trees) thrive and reach reproductive status is thus a key component in building resilience over time. Ecosystems can be greatly altered when key species are lost (see Elmqvist et al. 2003, and references therein) or they become dominated by new species (Vitousek and Walker 1989). Buffering the system against these perturbations is also important to maintaining a developmental trajectory.

3 ECOLOGICAL AND ANTHROPOGENIC DISTURBANCE IN THE OIL SANDS

3.1 Ecological Disturbances

3.1.1 *Fire*

The vast majority of the Lower Athabasca Region lies within the boreal forest, characterized by deciduous-leading, coniferous-leading, and mixedwood forests. Wildfire is the dominant ecosystem disturbance agent in the region. Empirical data on fire return intervals are highly variable, ranging from 40 to 250 years (Smith and D'Eon 2006). At least some of the extended variation is an artifact of fire suppression activities. When this factor is corrected, return intervals are typically less than 100 years (Andison 2003, Smith and D'Eon 2006). Fire return intervals also vary by topographic position, ecosite, and ecosite phase. Fires are characterized by their frequency and intensity, the combination of which, at the stand-level, determines community structure and productivity.

At the landscape-level, fires are the dominant natural process responsible for the large-scale patterns of vegetation and associated habitat. From a timber perspective, wildfires are a negative event due to the economic losses that are incurred. From an ecological perspective, however, wildfires are a source of renewal when their frequency and intensity are within the resilient capacity of the affected forest. Extremely hot fires or fires that recur too frequently though can degrade site quality by consuming forest floor and soil organic matter (Bormann et al. 2008) and/or trigger fundamental changes in community composition. In the latter case, for example, when two severe fires occurred in Minnesota within 10 years, there was a shift in species dominance from jack pine (*Pinus banksiana*) to trembling aspen (*Populus tremuloides*) because the second fire consumed the crop of jack pine propagules (Heinselman 1973; see Drever et al. 2006, for further examples). Fire frequency is predicted to increase through this century in conjunction with increasing temperatures due to climate change (Krawchuk et al. 2009; see s. 3.2.7) increasing the probability of fundamental changes in community composition.

One potentially significant and largely unknown hazard is the extent to which the peat:mineral mix used as the rooting substrate (which has a high organic carbon content relative to natural soils) is susceptible to ground fire during drought conditions. Combustion in organic soils is well documented and a relatively common event in the southern US, where frequently burned uplands are in proximity to wetlands (Snyder 1991). These fires are a result of smoldering combustion and can burn for many months resulting in almost total consumption of organic material (de Groot 2012). There is also evidence these fires can maintain themselves over winter below the soil surface (Benscoter et al. 2011). Smoldering fires are notoriously difficult to extinguish (Watts and Kobziar 2012). Over the long-term, organic fires can eventually consume or kill almost all live roots resulting in complete vegetation destruction.

3.1.2 *Insects and Pathogens*

Mortality from insects and pathogens is ubiquitous in the boreal forest[10]. Typically, rates of mortality tend to be low, at least on a landscape-scale, though localized outbreaks do occur. Forest tent caterpillar and spruce budworm are two principal defoliating insects of the boreal mixedwood forest (Smith and D'Eon 2006) though there are others (see Peterson and Peterson 1992, for examples). Tent caterpillar numbers tend to cycle over a period of about 14 years (Roland 2000). During an outbreak caterpillars can cause complete defoliation of trembling aspen leading to a reduction in incremental growth. Repeated defoliation also increases the risk of tree mortality (Hildahl and Reeks 1960).

Other insect species include Satin moth (*Leucoma salis*) and Aspen Tortix (*Choristoneura conflictana*), both of which impact aspen and poplar (Peterson and Peterson 1992). One new and potentially deleterious insect to mature and semi-mature jack pine (*Pinus banksiana*) in the Athabasca region is Mountain Pine Beetle (MPB; *Dendroctonus ponderosae*)[11]. To date, the predominant host of the beetle was lodgepole pine (*Pinus contorta*). British Columbia has experienced a massive beetle outbreak since the 1990s that devastated mature pine stands throughout the province. Beetles were detected in west-central Alberta for the first time in June 2006, and in 2009, another long-distance disbursal carried beetles from British Columbia into Alberta. Although most beetles disbursed into the same area, they were also detected farther east and in higher numbers suggesting an imminent spread in the population. MPB is capable of attacking jack pine though its reproductive capacity and population viability within this host are unknown.

Pathogens are generally not considered a major disturbance factor within the Al-Pac FMA area (Smith and D'Eon 2006). Species of concern include Armillaria Root Rot (*Armillaria ostoyae*; all commercial tree species), Shepherd's Crook (*Venturia* species) and Aspen Trunk Rot (*Phellinus tremulae*), the latter two of which affect both aspen and poplar.

Evidence suggests that species diversity confers resilience against insects and pathogens at the stand and landscape level (Thompson et al. 2009). In this respect, Jactel et al. (2005) showed that the effect of invasion and herbivory was significantly higher for planted monocultures versus mixed-species stands. That monospecific stands are fairly common in boreal mixedwoods, however, suggests they possess a long-term resilience, despite potentially high susceptibility to damage in the short-term (Thompson et al. 2009).

3.1.3 *Drought*

Drought-related mortality can be substantial in terms of scale and severity (van Mantgem et al. 2009), of which there is ample evidence in boreal forests (Hanna and Kulakowski 2012, Hogg et al 2002, 2008). There is some debate, however, as to whether drought is actually the direct and sole cause of mortality (McDowell et al. 2008), or whether predisposing factors (poor edaphic

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[10] See http://srd.alberta.ca/LandsForests/ForestHealth/ForestPests/Default.aspx

[11] See http://mpb.alberta.ca/

position, for example) and contributing factors (for example, pathogens) are also necessary (Manion 1991).

3.1.4 *Wind*

Only occasional and small wind events (individual or groups of trees blown over) have been reported within the forests of the Al-Pac FMA area, resulting in salvage operations within affected stands (Smith and D'Eon 2006). While this may be the case in older established natural stands, reclaimed sites may be much less resilient initially when trees are younger because roots are not well anchored, if root penetration is restricted by an impenetrable subsoil, or if the subsoil has a loose structure with reduced capacity to bind roots (tailings sand, for example). In this respect, it should be noted that wind throw risk in natural stands was considered to be site-specific (Smith and D'Eon 2006), suggesting that physical features are a factor that should be included in assessing site suitability for reclamation.

Wind is not considered a significant disturbance factor at a landscape scale within the Al-Pac FMA area. For example, over a 10-year period (1996 to 2006) no major catastrophic wind events occurred within the FMA (Smith and D'Eon 2006). This is a relatively short period to draw firm conclusions, however. One possibility is that the frequency and intensity of these events may increase over the next decades as the climate continues to warm.

3.1.5 *Invasion by Non-local Species (Native and Non-Native)*

Establishment of non-native plant species is problematic worldwide. Species that have become established in areas outside their natural range are termed 'alien species'. Alien species do not necessarily pose a significant risk to natural communities. This point is reflected in the 2011 *Weed Control Act*[12], which provides a listing of weed species in two categories, noxious weeds and prohibited noxious weeds. Under provisions of the Act, 'a person shall control a noxious weed that is on land the person owns or occupies' (Part 1, section 2) while 'a person shall destroy a prohibited noxious weed that is on land the person owns or occupies' (Part 1, section 3). Oil sands operators will thus be responsible for ensuring that reclaimed parcels do not become dominated by noxious weeds but will need to eliminate any prohibited noxious weeds.

Typically, species become invasive because edaphic conditions are well suited to their autecology (niche availability) and/or inhibitory to the growth and development of other plant species. Once invasives are established, growing space can be sufficiently limited for any other species that the ecosystem is, for all intents and purposes, self-sustaining (a grassland or shrub-dominated community, for example). Hence, desired patterns of stand development or succession may not be achieved (Kimmins 1997, 2007). Ecosystems of low inherent productivity tend to be susceptible to dominance by one or a few species. Invasion can also

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[12] See http://www.qp.alberta.ca/1266.cfm?page=W05P1.cfm&leg_type=Acts&isbncln=9780779760602

occur in highly productive ecosystems, however, either because native species have low recruitment due to insufficient propagules or recruits are simply outcompeted.

Invasion appears to be correlated with disturbance, and it has been hypothesized that fire and forest management reduce the capacity of natural forests to resist invasion, acting through fragmentation, degraded habitats, and altered moisture conditions (Sakai et al. 2001). As a highly disturbed environment, the establishment of alien plants (most of which will be either noxious or prohibited noxious weeds) within oil sands reclaimed lands is highly likely. An abundance of alien plants could significantly hinder establishment of native flora, with the result that anticipated patterns of stand development might not be realized in a timely fashion, or perhaps at all. Hence, reclaimed communities may not develop the species complement characteristic of natural non-mined stands.

Invasions can also have positive effects on ecosystem processes. Liao et al. (2008) found that invasion usually had a positive impact on carbon sequestration rates and both positive and negative effects on nitrogen cycling. This introduces a potential paradox because the presence of weeds has the potential to enhance resilience by increasing functional diversity and productivity (see s. 4.2). Their proliferation, however, could disrupt ecosystem development.

3.2 Anthropogenic Disturbances (Direct and Indirect)

3.2.1 *Erosion*

Erosion refers to the unintended transport and deposition of sediments by flowing water or wind, and can occur on a range of scales and intensity (see McKenna 2002, for a review of associated terminology). Erosion of constructed landforms is among the most common impediments to successful reclamation (McKenna 2002). On oil sands mine sites, drainage failure is one of the principal threats to the integrity of reclaimed landscapes, often leading to severe problems with erosion (McKenna 2002, Sawatsky and Beckstead 1996). Evidence suggests that erosion risk and severity is significantly greater in the absence of vegetation, though in one study on a Suncor sand disposal area almost a quarter of gullies occurred in areas that were vegetated (Sawatsky and Tuttle 1996).

3.2.2 *Soil Structure and Related Physical Properties*

Soil structure affects root penetration and the availability of water, air, and nutrients to plants. It is strongly influenced by soil texture, organic matter content, composition of exchangeable cations, freeze/thaw cycles, the binding effects of fungal hyphae and living roots, and aggregation through soil fauna (Bal 1985, Tisdal and Oades 1982). Soil micro-aggregates are more resilient to disturbance than macro-aggregates (Tisdal and Oades 1982). Faunal diversity is considered indicative of soil function (Bal 1982, Pawluk 1985, Rusek 1985). Poor soil structure can result in unstable slopes, and the lack of soil structural stability reduces the supporting capacity of soils for plant growth. Shallow soil depth, unstable sandy materials, and the presence of impervious layers may weaken the basic features that the soil provides to vegetation – anchorage, moisture and nutrient supply. In a synthesis of oil sands mine reclamation research, Barbour et al. (2007) concluded that when properly applied, reclaimed soils exhibit soil physical properties not significantly different from similar textured soils in undisturbed areas. MacKenzie has provided a comprehensive review of soil handing practices to aid mine operators in optimizing the use of available reclamation materials (Alberta Environment and Water 2012).

3.2.3 *Salinity and Sodicity*

Salts are created as a byproduct of the bitumen extraction process and from oxidation of reduced sulfur in saline sodic overburden (Wall 2005). Salinity and sodicity in soils are detrimental to plant growth (Howat 2000) and can have a strong effect on community composition (Purdy et al. 2005). Excessive concentrations of soluble salts, such as sodium and magnesium sulfates, in the rooting zone negatively affect the bioavailability of soil water, root functions and lifespan, and reduce bioavailability of phosphorus and most micronutrients (Renault et al. 1998, 1999). The water holding capacity and moisture release of the peat-mineral mix used as the rooting matrix in reclamation is important for mitigating salt migration into the upper layers of soil cover. Rising water tables or root penetration, however, can bring roots into contact with saline water.

3.2.4 *Contaminants (Residual Bitumen, Naphthenic Acids)*

Naphthenic acids are a byproduct of the bitumen extraction process and thus are concentrated in the water saturated mineral matter, collectively referred to as tailings (Scott et al. 1985). Residual bitumen refers to the bitumen remaining in the mine tailings from incomplete processing of the oil sands material itself (see Ferguson et al. 2009). These chemicals are toxic to many micro and macro organisms (Kavanagh et al. 2013, Nero et al. 2006), as well as plants (Baker 1970). In the latter group, they inhibit root hydraulic conductivity and gas exchange (Kamaluddin and Zwiazek 2002).

3.2.5 *High Soil pH*

High soil pH is often associated with saline and sodic conditions, features common in overburden and process water (see s. 3.2.3). High soil pH reduces bioavailability of phosphorus and most micronutrients (Brady and Weil 1999, Zwiazek et al. 2012).

3.2.6 *Low Soil pH*

Low pH in precipitation is produced from the sulfur (SO_2) and nitrogen (NOx) emissions generated as part of the oil sands extraction process, which combine with water to form sulfuric acid (H_2SO_4) and nitric acid (HNO_3), respectively. According to work by Whitfield et al. (2010), soils in the oil sands region tend to have low weathering rates and thus are acid sensitive (have low critical loads) when textures are coarse (see also McDonald 2008). Monitoring results indicate that soils in the region with higher acid deposition rates may be showing signs of acidification (McDonald 2008, Visser 2006). Effects of acidification include tree species mortality, decreased forest productivity, leaching of soil nutrients such as Ca^{2+} and Mg^{2+}, and root damage from aluminum and manganese toxicity. The molar ratio of Ca/Al in soil solution can be used to assess the risk of damage from acid deposition to vegetation (Cronan and Grigal

1995, Godbold et al. 1988). Secondary effects include increased vulnerability to cold temperatures, insect herbivory and disease (see McDonald 2008 and references therein).

3.2.7 *Climate Change*

The boreal forest biome is predicted to undergo the greatest increase in temperature compared to other biomes under climate change scenarios (IPCC 2007). Climate model outputs over this century for the region indicate warmer annual temperatures, warmer and shorter winters, and protracted growing season moisture deficits (though late in the century, total precipitation is projected to increase; Barrow and Yu 2005). Many of the disturbance risks and their severity are vulnerable to climate change. A warmer climate has greater potential energy, which is likely to result in extreme weather events that are more frequent and severe. As Thompson et al. (2009) note, "any ecosystem may change states when disturbed by a novel and/or severe disturbance, under altered interval time between disturbances, or with multiple simultaneous disturbances. Climate change may present such a serious challenge to the resilience of forest ecosystems globally".

Given that as ectotherms, insect survival and developmental rates increase with temperature their populations have substantial growth potential in a warming climate. Tree insect pathogens may thus become problematic; a current example is the Mountain Pine Beetle epidemic described previously (see s. 3.1.2, also Carroll et al. 2003, Logan and Powell 2001).

Climate change is also anticipated to impact community composition. Drobyshev et al. (2013) argue that species-specific responses to environmental variability imply that tree responses to climate change will likely not be synchronized among species (see also Welham 2010), which will alter the structure and composition of future forest communities. These changes are related to differences among species in regeneration, growth, competitive and migration abilities (Hansen et al. 2001, Mohan et al. 2009, Welham 2010, Welham and Seely 2011).

4 FACTORS THAT CONFER RESILIENCE

Providing a listing of disturbance types and their respective implications for ecosystem resilience is a useful starting point. It is critical to be aware, however, that resilience to a given perturbation is not a static property. For example, a jack pine-dominated stand is a fire-origin ecosystem very susceptible to fire – it has low inertial stability (resilience) to fire. However, because its canopy seed bank is contained within serotinous cones, a mature stand will rapidly be re-colonized by another pine stand – it has high elastic stability (resilience). Conversely, mature pine is susceptible to bark beetle attack, i.e., it has low inertial stability with respect to this insect, whereas a young pine stand tends not be attacked – it has greater inertial stability. Jack pine stands of all ages, however, have a high resilience against drought. Ironically, because fire or insect-killed pine stands are rapidly re-colonized following disturbance, these stands have high resilience only as long as these stand-replacing disturbances continue to occur. Pine stands have low resilience in the absence of such disturbance because they will slowly be replaced by later successional species (white spruce and balsam fir). How one assesses resilience then, depends on the type of perturbation and features of the community.

In more general terms, conferring resilience in ecological systems requires an answer to the question, "Resilience of what to what?" (Carpenter et al. 2001). This means identifying the relevant structuring variables, such as nutrient availability and salt inputs, disturbances (fire, wind, pathogens), and climate, that drive and reinforce alternative states of the system (e.g., grassland, shrub-dominated, or tree-dominated communities), and the spatial and temporal scales over which those variables operate (Carpenter et al. 2001, Holling 1992, Peterson et al. 1998). In short, the 'of what' component is the state(s) and spatial scale of the system, while perturbations (disturbance) that affect persistence and the temporal scale of interest are 'to what' the system has resilience (Drever et al. 2006). In the case of upland reclamation, the temporal scale could be as little as two decades, the period at which a site might be eligible for reclamation certification.

In this section, three approaches will be described for addressing the physical, chemical and biological characteristics (structure, composition, function) of reclaimed upland sites that would confer resilience to the range of ecological and anthropogenic disturbances identified above. From the general to the specific, these focus on (1) general ecosystem attributes (s. 4.1), (2) functions that need to be maintained (s. 4.2), and (3) attributes that confer resilience against specific perturbations or stressors (s. 4.3).

4.1 General Attributes of Resilient Ecosystems

Peterson et al. (1998) have suggested that resilience is generated by diverse, overlapping function within a scale and by redundant species that operate at different scales (see also Lundberg and Moberg 2003). Biodiversity can stabilize ecological systems by functional complementarity, with different species thriving under different conditions thereby buffering the effects of environmental change (Walker et al. 1999). There is an extensive literature on correlative relationships between ecological diversity and resilience (MacDougall et al. 2013, Petersen et al. 1998). Much of the experimental work, however, has been conducted in controlled laboratory conditions. In a recent paper, for example, Steudel et al. (2012) measured the biomass of microalgae grown in microcosms along two stress gradients, heat and salinity. They found that positive effects of biodiversity on ecosystem functioning decreased with increasing stress intensity in absolute terms but in relative terms, increasing stress had a stronger negative effect on low-diversity communities. **The implications for oil sands reclamation are that more diverse biotic communities are functionally less susceptible to environmental stress.** Steudel et al. (2012) provide a series of simple equations to define stress, stress-response intensity, biodiversity effect and stress-response buffering effect, and provide a review of experimental studies used to quantify these variables. This approach may have utility in evaluating resilience in reclaimed ecosystems.

One important consideration in the diversity-stability hypothesis is that "because anthropogenic changes often affect stability and diversity simultaneously, diversity-stability relationships cannot be understood outside the context of the environmental drivers affecting both. This shifts attention away from diversity-stability relationships toward the multiple factors, including diversity, that dictate the stability of ecosystems" (Ives and Carpenter 2007). Nonetheless, it is useful to determine the diversity of species within different functional groups because this information provides an indirect measure of ecosystem resilience (Peterson et al. 1998). As Levin (1998) has pointed out however, this is a necessary but not sufficient condition to establish resilience because not all species are of equal importance in maintaining system functions (and, hence, resilience). Paine (1966) coined the term keystone species, in reference to species that play roles in the dynamics of their communities disproportionate to their numbers (Petersen et al. 1998, Walker 1992). Such species play a critical role in maintaining the structure of an ecological community, affecting many other organisms in an ecosystem and helping to determine the types and numbers of various other species in the community. In boreal mixedwood communities, for example, aspen (*Populus tremuloides*) could be considered a keystone species, particularly within the context of reclamation. As a deciduous species, its leaves are shed annually thereby contributing to soil quality and the seasonal changes in light profile can promote understory development. Its rapid growth contributes to structural diversity.

Loss of a keystone species can trigger nonlinear responses that lead to cascades of local extinction and a fundamental change in the nature of the ecosystem (ecosystem resilience is thus reduced). In the case of oil sands reclamation, the converse may be equally applicable: **the absence of keystone species may inhibit the processes associated with community development and that promote resilience leading to greater uncertainty in system outcomes.**

4.2 Resilience in Terms of Functional Attributes

Species diversity *per se* is not the only feature related to ecosystem stability and resilience. The concept of functional groups is also important, whereby critical ecosystem processes are mediated by a particular set of species (Levin 1998). In this respect, Elmqvist et al. (2003) suggest that resilience is positively related to the diversity of functional groups within an ecosystem, as well as the species diversity within those groups, the latter of which they define as ‘response diversity’ (see Mori et al. 2013, for a review of this concept). One example is the group of microbial species that fix nitrogen or are involved in nitrification and denitrification; they control processes (in this case, nutrient cycling) that are fundamental to the persistence of ecosystems. Another key functional group is mycorrhizae. These fungal species form a (usually) mutualistic relationship with the roots of vascular plants. As Poscente and Charette (2012, and references therein) have indicated, mycorrhizal associations improve nutrient and water uptake, and mitigate the toxic impacts of metals and salts. Walker et al. (1999) provided evidence from an Australian savanna community that the presence of functionally similar species provided resilience against environmental variability. This was because different species varied in their tolerance to a given perturbation.

Puettmann et al. (2013) argue that managers need to identify those ecosystem functions crucial to achieving long-term objectives and the most likely disturbances or stresses that may interfere with those functions (as per s. 3). Species should then be grouped according to traits that relate to ecosystem function, as well as an ecosystem’s ability to respond to change (see Norberg and Cumming 2008). In this respect, Walker et al. (1999) classified dominant and minor plant species into functional types according to similarities in their attributes. Many of these functions and attributes are relevant to oil sands reclamation (see Table 1). Rowland et al. (2009) compared measures of ecosystem function (bioavailable nutrients, plant community composition, litter decomposition rate, and development of a surface organic layer) for reclamation treatments of several age classes with a range of natural forest ecotypes to discover which treatments had created ecosystems similar to natural forest ecotypes and at what age this occurred. In practice, only five plant attributes that were (a) easily measured, and (b) are related to the functions important for global change, were utilized by Walker et al. (1999): height, mature plant biomass (estimated by lateral cover), specific leaf area, longevity, and leaf litter quality (estimated by leaf coarseness).

Table 1. Potential functional and attribute lists that confer resilience (after Walker et al. 1999).

Global function	Associated plant functions	Associated plant attributes
Carbon and nitrogen cycling	Net amount of C fixed and stored per year; maximum carbon storage; seasonal changes in carbon storage; annual nitrogen releases from litter; nitrogen retention in plants; nitrogen fixation rate.	Relative growth rate [can be approximated by specific leaf area]; maximum total biomass (on a per-hectare basis); deciduousness; longevity (annual, biennial, and perennial growth forms); growth phenology; plant architecture (for example, height); N-fixing capacity; leaf litter quality (for example, nitrogen-carbon or lignin-nitrogen ratios), which determines the rate of litter decomposition and therefore release of both carbon and nitrogen.
Water budget	Total transpiration; water uptake by roots from different soil layers.	Water-use efficiency; transpiration rate; rooting depth; root distribution in profile.

Models of nutrient cycling have shown that resilience increases as the mean number of cycles that nutrient (or other mineral) atoms make before leaving the system decreases, i.e., the shorter the residence time, the more resilient is the system (DeAngelis 1980). This may be because the nutrient cycling rate dictates how much organic and inorganic components are available for organisms to persist in an ecosystem (Davidson et al. 2004, Feldpausch et al. 2004). Hence, nutrient cycling rates and microbial diversity are important functional attributes.

4.3 Attributes that Confer Resilience Against Specific Perturbations or Stressors

This section provides guidance on those characteristics that might be anticipated to confer resilience against specific perturbations or stressors. These are listed in Table 2. The top three characteristics that confer ecological resilience in oil sand upland reclaimed ecosystems are:

1. Species diversity, with a particular emphasis on functional diversity
2. A quality rooting zone
3. Minimize nitrogen and sulfur deposition.

Table 2. Attributes that confer resilience against specific perturbations or stressors

Perturbation or stressor	*Resilience objective*	*Attributes that confer resilience*[1]
Fire	Minimize outbreak risk	Deciduous-dominated stands
	Ecosystem recovery	Nutrient and moisture availability Species matched to edatopic position Good quality rooting zone
Insects and pathogens	Avoid epidemics	Landscape mosaic of stands with variable overstory composition
Drought	Avoid mortality	Species matched to edatopic position High available water holding capacity
Wind	Avoid windthrow	Closed canopy stands Well-developed root structure
Erosion	Avoidance	Contoured landscapes (minimize steep slopes, and long unbroken reaches) Stable vegetation cover Well-developed root structure
Poor soil structure and physical properties	Avoidance	Appropriate soil bulk density Deep and/or clean soil cover Well-drained soil
	Amelioration	Plant establishment tends to improve soil properties Deciduous plant species enhance soil organic matter

Perturbation or stressor	*Resilience objective*	*Attributes that confer resilience*[1]
Salinity	Avoidance	Deep and/or clean soil cover Well-drained soil Deep water table
	Tolerance	Species/provenances tolerant to saline/sodic conditions
Contaminants (bitumen, naphthenic acids)	Avoidance	Deep and/or clean soil cover
Low pH	Avoidance	Good soil buffering capacity (high organic matter content)
	Tolerance	Acid-tolerant plants
High pH	Avoidance	Deep and/or clean soil cover
	Tolerance	Salt-tolerant plants
Invasive species	Prevention and if required, elimination	Well established, productive and diverse populations of desired species
Climate variability and climate change	Adaptation	High species, genetic and functional diversity within and among reclaimed communities

[1] see Table 3 for guidance documents.

5 MANAGING FOR AND MEASURING RESILIENCE

5.1 Managing for Resilience

Managing for resilience may be achieved by implementing reclamation practices and procedures that maximize the probability a given desired state will emerge or persist over the time period of interest. As noted earlier, a system state can refer to a particular stand or community type, or a successional sequence (see Figure 1, for example).

The underpinning of resilient ecosystems is a rooting zone conducive to plant establishment and productivity, with a functionally diverse community (both above and belowground) to maximize the potential that development will be maintained along desired trajectories. Both components constitute the basis for deriving management activities that will confer resilience in upland reclaimed ecosystem (see Drever et al. 2006). Following Elmqvist et al. (2003), managing for resilience is to promote both functional diversity and species diversity within functional groups ('response diversity'; see s. 4.2). It is important to note that diversity includes not only a range of species but also includes the genetic complement (variability) of species. Conventional wisdom is that the genetic pool used to re-establish plant populations should be derived from locally adapted seed sources or provenances (Leimu and Fischer 2008). In the case of reclamation, this may be problematic if conditions vary considerably from natural ecosystems. Kulpa and Leger (2012), for example, showed that in established plants of a perennial grass, adaptive traits on restored sites were opposite to the criteria generally considered to be best suited to these conditions. This suggests that reclamation may have greater success if material can be identified that performs well under those specific conditions rather than based solely on local provenance (see Kulpa and Leger 2012, and references therein). Landhausser et al. (2012) have begun this process in the oil sands with respect to variation in the field performance of aspen on boreal reclaimed sites. Nevertheless, **ensuring that the plant material used in reclamation is genetically diverse (using both local and non-local sources, and from a range of parental stock) should be a priority.** Diverse ecosystems also appear to be more productive; more diverse tree canopies (in terms of species) have higher growth rates, regardless of successional status (Casperson and Pacala 2001).

Disturbance is ubiquitous in forests and is fundamental to forest renewal. In principle, the challenge is ensuring the resilient capacity of the reclaimed ecosystem can accommodate the historical disturbance regime: the type, frequency and intensity of past disturbance events. Any change in the disturbance regime has the potential to alter patterns of development and thereby compromise long-term objectives. The byproducts of bitumen extraction and processing, for example, generate materials in amounts and concentrations that represent unique challenges in reclamation (see s. 3.2, and Table 2). There is also evidence that ecosystems are not resilient to chronic stress (see Gunderson and Holling 2002), which inevitably disrupts core functions sufficiently to trigger a fundamental reorganization of the ecosystem. Once a new equilibrium (stability domain) has been achieved, experience shows it can be very difficult to shift the ecosystem into an alternative, and presumably more desirable, state.

To create resilient ecosystems, management must focus on both mitigative and adaptive strategies. Mitigative actions confer resilience by eliminating or reducing exposure to chronic stresses (nitrogen and sulfur deposition, salt intrusion, for example), and providing good landform design and materials placement. The adaptive approach focuses on traits that allow plant species to tolerate chronic or periodic stress, or that predisposes them to accommodate disturbance and the impacts of a changing climate. Table 3 lists management practices to promote the development of characteristics that confer resilience in reclaimed ecosystems.

Table 3. Management practices to confer resilience in reclaimed upland ecosystems

Perturbation or stressor	*Characteristic that confers resilience*	*Management practice*
Fire	Deciduous-dominated stands (minimize risk)	Consult *Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region*[1] for planting guidelines.
	Good nutrient and moisture availability (post-fire recovery)	Consult LCCS[2] and BMP[3] guidelines for soil handling procedures. Possible application of fertilizer to enhance productivity[4].
	Species matched to edatopic position (post-fire recovery)	Consult *Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region* for planting guidelines.
	Good quality rooting zone (post-fire recovery)	Consult LCCS and BMP guidelines
Insects and pathogens	Landscape mosaic of stands with variable overstory composition	Construct a diversity of landforms that constitute the basis for plant communities. Consult *Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region* for planting guidelines that ensure plant communities match edaphic conditions and that a diversity of stand types are planted. Apply LFH[3] to enhance diversity.

Perturbation or stressor	*Characteristic that confers resilience*	*Management practice*
Drought	Species matched to edatopic position	Consult *Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region* for guidance.
	High available water holding capacity (AWHC)	Consult LCCS and BMP guidelines to ensure soil depths are adequate, and additional options (layering, for example). Higher organic matter content improves AWHC.
	Proximity of water bodies to upland sites	Integration of uplands and wetlands in landscape design.
Wind	Closed canopy stands	Ongoing monitoring to ensure full stocking.
	Well-developed root structure	Ensure good quality rooting zone[1,3].
Erosion	Stable vegetation cover	Apply LFH to promote rapid and diverse plant establishment.
	Well-developed root structure Minimize slope steepness Minimize path length of surface flow	Ensure good quality rooting zone[1,3]. Proper landform design.
Poor soil structure and physical properties	Minimize or mitigate limiting factors	Ensure good quality rooting zone[1,3]. Apply LFH to promote rapid and diverse plant establishment.
Salinity	Deep and/or clean soil cover Deep water table Species/provenances tolerant to saline/sodic conditions	Consult LCCS and BMP guidelines to ensure soil depths are adequate. Consult *Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region* for guidance.

Perturbation or stressor	*Characteristic that confers resilience*	*Management practice*
Contaminants (bitumen, naphthenic acids)	Deep and/or clean soil cover	Consult LCCS and BMP guidelines.
Low pH	Good soil buffering capacity (high organic matter content) Acid-tolerant trees and plants	Fertilize to promote growth (organic matter). Consult *Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region* for guidance. Minimize nitrogen and sulfur emissions.
High pH	Deep and/or clean soil cover Salt-tolerant plants	Consult LCCS and BMP guidelines. Consult *Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region* for guidance.
Invasive species	Well established, productive and diverse populations of desired species	LFH application. Fertilize to promote growth of desired species[4]. Control invasive species[1].
Climate variability and climate change	High biodiversity within and among reclaimed communities, high genetic diversity	Consult *Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region* for planting guidelines and ensure a diversity of stand types are planted. Apply LFH to enhance diversity. Introduce species from outside of region that are adapted to potential future climatic conditions. Ensure populations are genetically diverse.

[1] Alberta Environment 2010. [2] Alberta Environment 2006. [3] Alberta Environment and Water 2012. [4] Rowland et al. 2009.

5.2 Measuring Resilience

Walker et al. (1999) sought a measure of resilience by identifying five plant functional attributes, height, biomass, specific leaf area, longevity, and leaf litter quality (see Table 1), that determined carbon and water fluxes. They assigned values for these functional attributes to each of the graminoid species in a lightly and a heavily grazed site in an Australian rangeland. Two measures of functional diversity were calculated. One measure was simply the number of attribute combinations that occurred within a community. The second was a standardized measure of the distance species were apart in attribute space, termed the ecological distance (see Walker et al. 1999, for details). From a comparative analysis between the two sites, Walker et al. (1999) were able to demonstrate that functional diversity was important in ensuring the persistence (resilience) of ecosystem function between the two environments. This approach has potential application to oil sands reclamation: (1) Functional attributes could be calculated on reclaimed sites as a means of assessing the development of resilience over time, and (2) A comparative analysis of functional attributes could be undertaken between natural and reclaimed sites to estimate equivalence.

Ruiz- Jaén and Aide (2005 a, b) evaluated restoration success by comparing four measures of vegetation structure, four measures of species diversity, and six measures of ecosystem processes among pre-reforested, reforested, and reference sites. This technique is amenable to oil sands reclamation and could be used to categorize species into functional types and as a means of comparing reclaimed and reference sites.

Carpenter et al. (2001) make the important point that to measure resilience one needs to define the time scale, with the choice of scale dependent of the issue under investigation. In the case of reclamation, relevant time scales could vary from several decades (the time period over which a reclamation certificate might be awarded) to a century, or more. The latter of which might be the time required to reveal the full characteristics of a reclaimed ecosystem in equilibrium with its environment. A key issue is that variables critical to resilience change over a broad range of time scales; fast variables (for example, insect outbreaks) are highly responsive and can show high inter-annual variability, while slow variables (for example, foliage accumulation in a forest, litter or soil carbon stores) require decades or longer before changes are significant (Carpenter et al. 2001). Often, it is the slow variables that modify the stability conditions for fast variables (see Gunderson and Holling 2002). Changes in slow variables can thus have a profound impact on ecosystem resilience. This led Holling and Gunderson (2002) to suggest that the minimal time to properly evaluate resilience in a given ecosystem should span a length of three generations in the longest-living species (longer if possible). In the boreal forest, fire return intervals can vary from 40 to 250 years, though for the latter case return intervals are typically less than 100 years when fire suppression is accounted for (see s 3.1.1). Following this logic would mean that resilience could only be properly evaluated empirically in as little as 120 years though it might require at least 300 years. From a reclamation perspective this time frame is impractical given that operators are seeking to acquire reclamation certificates on parcels that have been reclaimed for only several decades, or so (see below).

In principle, resilience could be predicted from models that incorporate the critical processes driving ecosystem productivity and community development (Carpenter et al. 2001). These models are likely to be highly complex and it seems unlikely that sufficient data would be available for their calibration, particularly within the reclamation setting. Nevertheless, models can play a useful role in identifying indicators that may signal ecosystem resilience and vulnerability.

Carpenter et al. (2001) provide examples with two case studies, one from the lake districts of North America and one from the rangelands of Australia. In the case of oil sands reclamation, Welham used the process-based hybrid ecosystem management model FORECAST to compare current and alternative reclamation practices. Specifically, ecosystem productivity was projected in relation to a broad range of variables, which can be considered as proxy measures of resilience: peat decomposition rates (Welham 2005a, b, 2006); the depth (Welham 2005a, b) and type (Welham 2005 b, 2006) of the capping material; nitrogen deposition (Welham 2006, unpublished); subsoil organic matter content (Welham 2006); species mixes (Welham 2005a), planting densities (Welham 2005a, 2006), understory dynamics (Welham 2005a, b, 2006), and dead organic matter dynamics (specifically snags; Welham 2005 b). A similar analysis has been undertaken with the FORECAST Climate model to determine the impact of climate change on the vulnerability (resilience) of natural and reclaimed ecosystems (Welham 2010, Welham and Seely 2011, in prep.).

Peterson (2002) used a system dynamics approach which he termed "probabilistic resilience," to allow landscape simulation models to be used to estimate resilience. A method called cross-scale edge was applied as an empirical approach for estimating resilience across a landscape. In brief, the method relies on the calculation of ecotones, which are the transitional areas between two stable states. Resilience is measured as the probability that a given state will persist over the time period of interest (see Peterson 2002, for details). Cross-scale edge is a simple measure of landscape resilience because it does not require a detailed understanding of the ecological dynamics of a region. Its simplicity makes the measure relatively easy to apply.

Designing and assessing resilience in reclaimed oil sands ecosystems will likely require a combination of empirical measures informed by model outputs. Models can be used to project the long-term consequences of a given reclamation prescription while specifying which particular ecosystem attributes are relevant to a monitoring program and the time frame when the requirements for a reclamation certificate could be met. In that respect, model outputs, ecological measures, and checklists which identify management activities, decisions and interventions should be developed collectively, and comprise a decision support system that can address the question ‘Does this reclaimed upland site possess or is capable of developing, characteristics of a resilient ecosystem?’

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7 GLOSSARY

7.1 Terms

Many of the following definitions were taken from Pyper, M.P., C.B. Powter and T. Vinge, 2013. *Summary of Resiliency of Reclaimed Boreal Forest Landscapes Seminar*. OSRIN Report No. TR-30. 131 pp.

Allogenic

Caused by factors in the environment that are largely independent of and external to the biotic community.

Alternative Stable State

An ecological condition that is different than the original (or desired) condition but is nonetheless stable (there is a balance in system processes).

[Wikipedia] In ecology, the theory of alternative stable states (sometimes termed alternate stable states or alternative stable equilibria) predicts that ecosystems can exist under multiple "states" (sets of unique biotic and abiotic conditions). These alternative states are non-transitory and therefore considered stable over ecologically-relevant timescales. Ecosystems may transition from one stable state to another, in what is known as a state shift (sometimes termed a phase shift or regime shift), when perturbed. Due to ecological feedbacks, ecosystems display resistance to state shifts and therefore tend to remain in one state unless perturbations are large enough. Multiple states may persist under equal environmental conditions, a phenomenon known as hysteresis. Alternative stable state theory suggests that discrete states are separated by ecological thresholds, in contrast to ecosystems which change smoothly and continuously along an environmental gradient.

Autogenic

Changes in the physical, chemical, and biotic environment that are produced by the resident organisms; self-generating.

Biogenic

Sudden disruption of allogenic or autogenic processes generated by living organisms.

Biological Legacy(ies)

Species, patterns, or structures (such as surviving trees that serve as seed sources, regenerative material like rhizomes, and nutrients) that act as sources of ecosystem recovery.

Complex Adaptive Systems

Macroscopic system properties such as trophic structure, diversity-productivity relationships, and patterns of nutrient flux that emerge from interactions among components, and may feed back to influence subsequent development.

Ecological Elasticity

The speed with which a system returns to a previous state after a perturbation.

Keystone Functional Group

A small set of species that control processes fundamental to the persistence of an ecosystem. The group has a larger role than individual keystone species.

Keystone Species

A species that influences community dynamics to an extent disproportionate to its numbers. Keystone species play a critical role in maintaining the structure of an ecological community, affecting many other organisms and helping to determine the types and numbers of various other species.

Mobile Links

Organisms that actively move in the landscape and connect habitats over space and time. These organisms can provide essential ecosystem processes, such as pollination and seed dispersal.

Panarchy

A conceptual framework built on the idea that ecosystems are interlinked in continual adaptive cycles of growth, accumulation, restructuring, and renewal.

Recovery

The return to a pre-existing condition.

Resilience (Ecological) – assumes multiple stable states are possible

The ability of a system to absorb perturbation before changing into a different state i.e., an alternate stable state.

The magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour.

The amount of disturbance that can be sustained [by an ecosystem] before a change in system control or structure occurs.

A measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.

The capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity.

The capacity of an ecosystem to return to the pre-condition state following a perturbation, including maintaining its essential characteristics taxonomic composition, structures, ecosystem functions, and process rates.

Resilience (Engineering) – assumes one stable state is possible (also called Resistance)

The capacity of a system to return to its pre-disturbance condition.

The time required for a system to return to its pre-disturbance equilibrium point following a disturbance event.

Resistance

The capacity of the ecosystem to withstand or absorb disturbances and not change its composition, structure, or processes significantly.

The capacity of an ecosystem (e.g., a forest) to resist minor disturbances over time, such as the death of a few trees or a chronic level of herbivory by insects.

The ease or difficulty of changing the system state (see Alternative Stable State).

Stability

The capacity of an ecosystem to remain more or less in the same state.

The capacity to maintain a dynamic equilibrium despite perturbation.

Support Areas

Landscape patches or habitats that maintain viable populations of mobile links.

Trajectory

The steps or path from one state to another (e.g., disturbed to reclaimed). Trajectories constitute expected stages of development, and thus they help identify characteristics that should be incorporated into a reclamation plan. Similarly they are useful in monitoring as a comparison between a site's current and expected status – deviations from an expected trajectory can be either remedied or a new end state can be predicted.

7.2 Acronyms

AWHC	Average Water Holding Capacity
BMP	Best Management Practices
CAS	Complex Adaptive Systems
FMA	Forest Management Agreement
LCCS	Land Capability Classification System
LFH	Litter, Fibric, Humic
MPB	Mountain Pine Beetle
OSRIN	Oil Sands Research and Information Network
SEE	School of Energy and the Environment
SLA	Specific Leaf Area

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