Risk and Uncertainty in Oil Sands Upland Reclamation: Best Management Practices within the Context of Climate Change

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REPORT SUMMARY

The focus of most climate change impact studies to date is on changes related to mean climate conditions. In terms of climate model output, these changes are more robust than changes in climate variability, the latter of which has considerably greater uncertainty. By concentrating on climate means, however, the full impacts of climate change are probably being seriously underestimated. This report discusses and illustrates how the risk and uncertainty introduced by climate change can be incorporated into reclamation planning.

Two approaches to reclamation planning are described. In the first approach, best management practices are developed using a deterministic methodology. A deterministic system is assumed to always produce the same output from a given starting condition or initial state. A corollary to this approach is that practices are geared to achieving the long-term average outcome. As long as this average satisfies management goals, variation is considered to be minimal and/or of little significance. The vegetation prescriptions provided in the Revegetation Manual are an example of a deterministic methodology. A fundamental assumption underpinning the validity of the approach is that past performance constitutes a reliable index of future performance. In the case of oil sands reclamation, this assumption is questionable for two reasons. First, oil sands reclamation soil materials possess biogeochemical properties and conditions that differ fundamentally from natural systems. Second, climate change is a source of uncertainty. It is anticipated to be a major chronic disturbance because of the northerly location of the oil sands.

In the second approach, reclamation planning is undertaken using a stochastic methodology. This approach assumes that system development occurs along a trajectory dictated by one or more random variables (decision points). Each decision point thus represents an opportunity for the system trajectory to be altered by changes in the value of its random variables. Climate and climate change are likely the most important random variables influencing the developmental trajectory of reclaimed ecosystems. In this respect, the impact of climate as a driver of ecosystem performance needs to be considered. Under a stochastic, risk-based approach, the two basic principles of reclamation planning are:

1. That it represents the balance between the probability of an undesirable outcome and the marginal improvement in outcome from an additional unit of investment (increased capping depths or higher planting densities, for example), and
2. The greater uncertainty in outcome, the more conservative should be the management inputs (i.e., the higher the level of effort).

One consideration in accounting for climate change is timescale. Over the next several decades, uncertainty in climate predictions will be predominantly a consequence of natural climatic variability. The relative effect of climate change increases significantly thereafter, which means the climate signature will become clearer and more predominant during the latter decades of this century. The implications for reclamation planning are that prescriptions suitable for establishing stands under current climate conditions may prove inadequate in the future, and short-term trends in vegetation performance may not be a reliable index of future performance. Changes in the disturbance regime associated with wildfire and insect epidemics are not given

explicit consideration in reclamation planning. These risks add considerable uncertainty to assumption that current practices will be suitable for achieving long-term objectives.

From a reclamation perspective, stand-level outcomes are a necessary prerequisite to successful reclamation, particularly if performance is focused on utilitarian metrics (merchantable volume, for example). Evidence suggests, however, that for the public at large, reclaimed areas are more likely to be evaluated in terms of their amenities, such as scenic beauty, ‘naturalness’, and recreational value – landscape-level attributes. The boreal mixedwood landscape has been characterized as a ‘mosaic’ of stands of differing age and species composition. At least part of this spatial heterogeneity will be created on mine sites because reclamation occurs progressively, which will ensure heterogeneity among stand ages. A second option for creating heterogeneity is to ‘plan for failure’ (PFF). Under a PFF strategy, stands are expected to vary in their developmental trajectories, with some stands transitioning to a different end land-use than originally intended. This variation constitutes the basis on which the desired level of heterogeneity is achieved. Another option is to actively manage for landscape heterogeneity by varying capping and planting prescriptions on a stand-by-stand basis. The advantages and disadvantages of these options are discussed. Changes in the disturbance regime (wildfire or insect epidemics) could largely render moot concerns around uncertainties in development trajectories.

A fundamental challenge to assessing current best management practices within the context of climate change is the questionable utility of relying on historical practices for guidance. The success of a particular reclamation prescription in meeting long-term objectives can, in principle, be assessed empirically. In practice, however, many years must elapse before a reclaimed stand has developed sufficiently that a given prescription can be evaluated definitively or that interim measures are a reliable proxy for long-term outcomes. Modeling of ecosystem development is perhaps the only practical approach to resolving to this dilemma.

There have been two basic approaches to predictive modelling of ecosystem response to a changing environment: empirical (statistical)- and process-based models. Here, a stochastic approach is described in which probability outcomes are derived for reclamation planning using the FORECAST Climate model and a state-and-transition model (STSM). FORECAST Climate is used to project vegetation development (i.e., ‘states’) for a given reclamation land unit (e.g., dry, moist rich, moist poor, wet rich, and wet poor) subject to current and alternative management options, disturbance regimes, and two climate change scenarios. The probabilities associated with each state transition are then be derived from these runs. The STSM simulates vegetation development for reclamation land units over time and across an entire mine footprint. By implementing a Monte Carlo experiment (i.e., repeated iterations through the STSM) in conjunction with the transition probabilities from FORECAST Climate, uncertainties in outcome for a given reclamation practice are assessed as a consequence of climate change.

Model output will permit stakeholders and regulators to evaluate the efficacy of current and alternative adaptation strategies with respect to mitigating risk of undesirable outcomes due to climate change. In addition, the STSM will be provided with the capability for geospatial representation of each land unit and land unit phase. This functionality will aid mine operators in meeting approval conditions regarding integration across lease boundaries and with undisturbed areas. The tool will also be useful for wildlife habitat planning and assessment of reclamation performance with respect to re-establishing wildlife habitat (both of which have a strong spatial component).

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The project lead is Dr. Clive Welham, with team members Dr. Brad Seely (University of British Columbia), and Leo Frid and Colin Daniel (Apex Resources Ltd., Ottawa, Ontario). A founding team member, Dr. Gillian Donald (Donald Functional & Applied Ecology Inc., Vancouver, British Columbia), departed after several months to accept a position as a First Nations representative within CEMA's Reclamation Working Group (RWG).

Valuable input and support to the project were provided by the members of CEMA's RWG and Integrated Task Group; Chris Powter, OSRIN Executive Director; Jennifer Ardiel and Mary-Ann Wilson, NRCan; Dr. David Bergstrom, Reclamation Research Specialist, Alberta Environment and Sustainable Resource Development; and Dr. Brett Purdy, Senior Director, Enhanced Ecology, Alberta Innovates – Energy and Environment Solutions.

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1 INTRODUCTION

There is a need in the energy sector to increase understanding with respect to how businesses and organizations manage risks and adapt to current and anticipated climate conditions. Documenting and sharing information about these practices will help promote standardization in the measures, tools, and information used as the basis for strategic decision-making. In the case of the Alberta oil sands, no quantitative landscape-level reclamation planning tools are yet available to operators to aid in the assessment of climate change uncertainties or the development of adaptation strategies to ensure successful reclamation of oil sands disturbances[1]. To this end, a regionally applicable tool is being developed that will improve consistency among operators and provide a means of assessing current best management practices. This work represents a component of a larger project entitled: *A tool for adaptation decision-making in oil sands reclamation under risk of climate change*. The project was funded under Natural Resources Canada's Enhancing Competitiveness in a Changing Climate Program. The project's principle objectives are to:

1. Improve the applicability of two established models that have been used to support adaptation decision-making within the context of oil sands reclamation – a state-and-transition simulation model (STSM; Frid and Daniel 2012), and the process-based forest ecosystem model, FORECAST Climate (Seely et al. 2014).
2. Develop a decision support tool (DST) by linking the STSM and FORECAST Climate.
3. Use the DST to evaluate best management practices for reclaiming upland sites in terms of climate-related risk exposure and then inform adaptation and management planning within the context of climate change at both the stand and landscape scale.
4. Produce a guidance document on how to implement the tools, interpret output, and assess the implications for reclamation principles and practices as reflective of an adaptive decision framework.

Work to date has focused on securing data necessary for application of the STSM and FORECAST Climate. Model results are preliminary and thus are not presented here. This report focuses on risk and uncertainty and how their consideration changes the approach to upland reclamation planning. The ideas presented herein form the conceptual framework on which the larger project is based. They also have broader application in oil sands reclamation (wetlands and tailings, for example) and in reclamation practices elsewhere.

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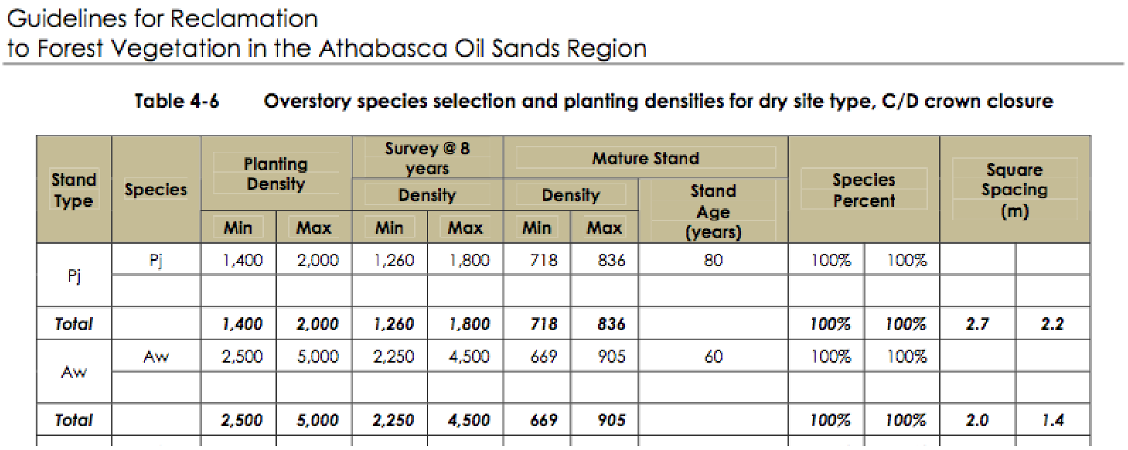
[1] For further reading on the topic of adaptation, consult the following:
http://esrd.alberta.ca/forms-maps-services/publications/documents/ClimateChangeAdaptationFrameworkManual-April%202010.pdf
http://esrd.alberta.ca/forms-maps-services/publications/documents/ATISC-TreeSpeciesAdaptationRisk-Dec2013.pdf
http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/earthsciences/pdf/assess/2014/pdf/Full-Report_Eng.pdf

2 RISK AND UNCERTAINTY IN UPLAND RECLAMATION

The vast majority of climate change impact studies to date focus on predicted changes in mean future climate conditions relative to mean conditions from a historical reference period. By concentrating on climate means, however, the full impacts of climate change are likely being seriously underestimated. An alternative approach is to incorporate potential changes in interannual climate variability. The challenge is that mean changes in climate are more robust than when climate variability is taken into account, the latter of which has considerably greater uncertainty. These two approaches are described and contrasted below, along with an illustration of how risk and uncertainty might change the traditional approach to reclamation planning. Consideration is then given to temporal and spatial impacts. The report concludes with an example of how models can be used to develop an approach to reclamation planning that takes a fuller account of climate change.

2.1 The Deterministic Approach

Traditionally, natural resource management has been practiced as though inputs and outputs are largely deterministic. In a deterministic system there are no stochastic elements involved in the development of future states. The system is thus assumed to produce the same output from a given starting condition or initial state. A corollary to this approach is that practices are geared to achieving the long-term average outcome. As long is this average satisfies management goals, variation is considered to be minimal and/or of little significance. The vegetation prescriptions provided in the Revegetation Manual (Alberta Environment 2010) are an example of this approach. As further illustrated in Figure 1, achieving a target crown closure class is deemed to require a minimum initial planting density. This density is then reduced over time by mortality events to a minimum density at stand maturity. The latter is assumed to be sufficient to achieve the crown closure target. Maximum tree densities at different stages in stand development are also provided (Figure 1). Technically, these densities are unnecessary since only a minimum density is required to reach the threshold target. They are provided as an indication of the upper limit to planting density, beyond which further increases generate diminishing returns and thus are economically inefficient.



Guidelines for Reclamation
to Forest Vegetation in the Athabasca Oil Sands Region

Table 4-6 **Overstory species selection and planting densities for dry site type, C/D crown closure**

Stand Type	Species	Planting Density		Survey @ 8 years		Mature Stand			Species Percent		Square Spacing (m)	
				Density		Density		Stand Age (years)				
		Min	Max	Min	Max	Min	Max					
Pj	Pj	1,400	2,000	1,260	1,800	718	836	80	100%	100%		
Total		***1,400***	***2,000***	***1,260***	***1,800***	***718***	***836***		***100%***	***100%***	***2.7***	***2.2***
Aw	Aw	2,500	5,000	2,250	4,500	669	905	60	100%	100%		
Total		***2,500***	***5,000***	***2,250***	***4,500***	***669***	***905***		***100%***	***100%***	***2.0***	***1.4***

Figure 1. A clipped section of Table 4-6 of the Revegetation Manual illustrating recommended planting prescriptions by site type.
Initial planting densities are deemed sufficient for achieving a C/D crown closure class (≥ 50%) at maturity. Canopy closure at maturity is considered a deterministic outcome of initial conditions (further details in text).

The attraction of a deterministic approach is its simplicity. Guidance documents provide clear and unambiguous procedures for achieving anticipated outcomes. These procedures are usually derived from empirical data and expert opinion in combination with experience gained through trial-and-error. In some cases, output from mechanistic models is also utilized (as was the case, for example, with the planting prescriptions provided in the Revegetation Manual).

A fundamental assumption underpinning the validity of this approach, however, is that past performance constitutes a reliable index of future performance. In the case of oil sands reclamation, this assumption is questionable for two reasons. First, oil sands reclamation soil materials possess biogeochemical properties and conditions that differ fundamentally from natural systems. In mine reclamation, underlying upland substrates are comprised of tailings sand often with residual salts or bitumen, or overburden that varies from saline-sodic to non-saline. Contaminants from oil sands process water might also be present. To render them suitable for reclamation, substrates are capped with a rooting layer comprised of a 30 to 50 cm mixture of peat and mineral soil (a peat:mineral mix), or a layer of upland surface soil (LFH plus mineral soil), either singly or in combination with a layer of non-saline overburden. The latter is used when the underlying substrate has properties unsuitable for healthy plant root growth. The extent to which these reclaimed 'soil' caps can be considered as analogous to natural materials in terms of vegetation performance, is an open question.

Climate change is the other key source of uncertainty with respect to past and future performance. Climate change is anticipated to be a major chronic disturbance in the oil sands region because of its northerly location (see, for example, Sauchyn and Kulshreshtha 2008). Climate in the region is cold continental (Rostad and Ellis 1972). Hence, summers are cool and winters cold; the historical mean daily summer (May to August) and winter (November to February) temperatures are 13 °C and -12 °C, respectively (Strong and Leggat 1991). The region also tends to be dry, with mean total summer and winter precipitation at 250 and 63 mm, respectively. At only 5 months in length (May to September), the growing season is of relatively short duration. Climate change in the Fort McMurray region is expected to result in warmer winters and longer growing seasons, though summer moisture deficits may be more severe (Barrow and Yu 2005). These climatic trends are reasonably consistent between various global circulation models, particularly late in this century. There is, however, a wide variation in the predicted precipitation response, both seasonally and in terms of overall amounts.

Historical conditions will almost certainly not be representative of the future and given that climate is the main determinant of regional net primary production (NPP; Peng and Apps 1999), predicting future vegetation response will also have its challenges. One possibility is that a warming climate could mitigate the cold soil conditions and short growing season that serve to limit NPP in northern ecosystems. Ecosystem production might therefore be improved overall. Model outcomes indicate a greater variability in climatic conditions (see, for example, Barrow and Yu 2005). Hence, severe drought, ice storm and snowfall events, wildfires and insect outbreaks may become more frequent, leading to intermittent but significant tree damage and mortality. These sources of uncertainty call into the question the ‘cause-and-effect’ relationships upon which the deterministic approach is reliant.

2.2 The Stochastic Approach

The stochastic approach assumes that system development occurs along a trajectory dictated by one or more random variables (decision points). Each decision point thus represents an opportunity for the system trajectory to be altered by changes in the value of its random variables. This is because a random variable can assume one of a range of possible values, each with an associated probability. As noted in the previous section, climate and climate change are likely the most important random variables influencing the developmental trajectory of reclaimed ecosystems.

There are three main components of uncertainty associated with climate change: the natural variability in climate, greenhouse gas (GHG) emissions, and climate model inaccuracies (see Charron 2014). At the very least, climate patterns will reflect the unpredictable natural fluctuations in climate variables that occur even without any change in GHG concentrations. One of the main drivers of climate change is the chemical concentration of the atmosphere (particularly greenhouse gases and aerosols). The evolution of anthropogenic GHG emissions, however, is highly uncertain, along with the fact that climate models all differ in their predicted responses to GHGs. It is also worth pointing out that predicted changes in temperature are closely tied to GHG emissions. Predicted patterns in precipitation, however, are linked to natural variability and are also specific to a given climate model (Charron 2014).

How does the stochastic nature and pattern of climate change affect the approach to reclamation planning decisions? Two factors need to be considered: the impact of climate on the main drivers of ecosystem productivity and secondly, on outcomes (end land-used objectives). Figure 2 illustrates these ideas by contrasting the deterministic and stochastic approaches using a hypothetical example of establishment densities at survey year 8 as a driver of crown closure (CC) at maturity.

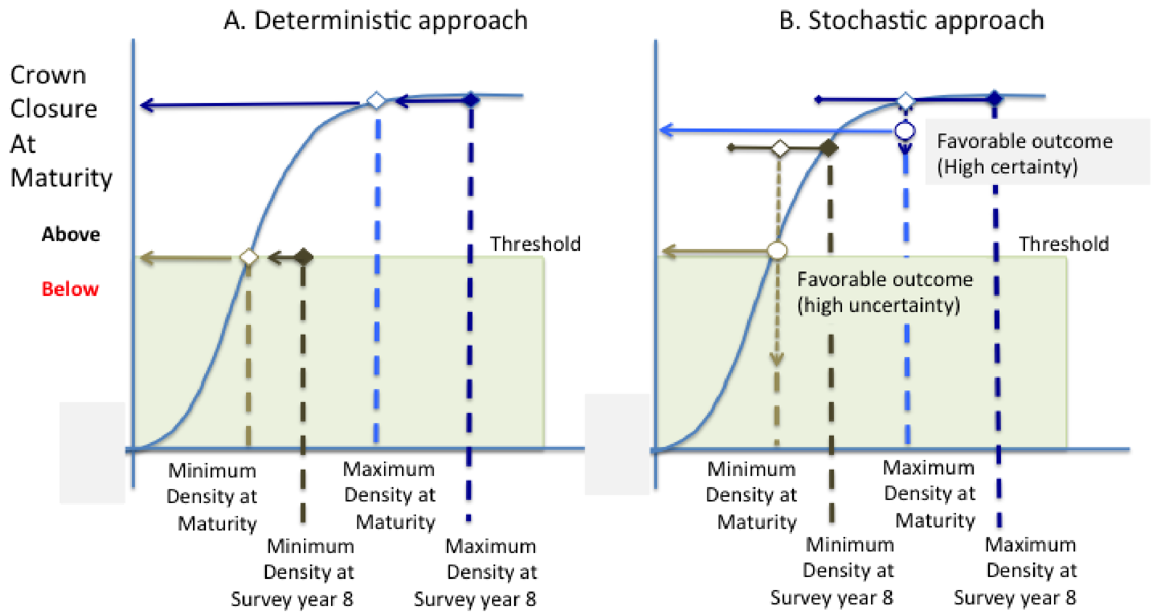


Figure 2. Predicted crown closure (CC) at maturity (blue line) as a function of establishment density at survey year 8 (solid diamonds).
The dark brown and blue dashed lines denote minimum and maximum densities, respectively.
In the deterministic approach (panel A), mortality reduces density to a fixed, average value (open diamond) at maturity, with a well-defined outcome.
The reduction in mature density in the stochastic approach (panel B) shows unidirectional decline with a mean value (open diamond). One source of that variation is climate. This generates variation in outcomes (vertical arrows), which in this case, is CC.
For maximum densities, the variation is minimal but at the minimum density, it generates outcomes that can be below a desired threshold (green shaded area).

In Figure 2A, the deterministic approach specifies a minimum and maximum density at the survey year that over time, is reduced by mortality. At maturity, densities are such that on average the minimum CC target is achieved. Figure 2A also shows CC when the maximum density is established.

The impact of variation in density at maturity is illustrated in Figure 2B. At the maximum survey density, this variation reduces the average CC but within a relatively narrow range. One way to interpret this result is that from a risk management perspective, planting the maximum density incurs minimum risk of not meeting the CC threshold (which could, for example, be considered an end land-use objective). This contrasts sharply with the minimum density. The CC target is indeed achieved, on average, but there is considerable variation around the mean. In about 50% of cases, the CC objective will not be met. Hence, from a risk management perspective, planting the minimum density introduces considerable uncertainty as to whether sufficient outcomes will satisfy the long-term objective.

A general case for the application of risk management to reclamation practices is developed in Figure 3. A level of effort is expended (the decision variable) that generates a response (or outcome). Typical response variables in upland reclamation are site index, tree volume, canopy closure, and species composition. Examples of the decision variable could include the depth of capping materials applied to create a rooting zone, and silvicultural activities to promote and maintain vegetation development. A common proxy for these activities is the financial costs expended in their implementation.

In interpreting Figure 3, the simplest cases are the two extremes in level of effort. Minimal effort generates an average response level well below the threshold that defines a successful outcome. Furthermore, variation in effort has little impact on achieving a favorable outcome. In risk management terms, an unfavourable response is expected with high certainty. From a stakeholder perspective, this level of effort and response would be deemed socially unacceptable. Very high levels of effort, in contrast, essentially guarantee a favorable outcome both in terms of average response and after accounting for variance (Figure 3). From an industry perspective, however, this would likely constitute an example of ‘overbuilding’ in that the financial expenditure required to achieve this level of certainty would be considered prohibitive. The crux of reclamation planning and decision-making then resides between these two extremes.

The general message is that accounting for uncertainty requires consideration of both the average (expected) response and its variation. Being successful ‘on average’ may not be socially palatable if the associated variation generates outcomes that are highly undesirable. By this reasoning, the deterministic approach is likely not sufficiently conservative because it does take account of the variance around the mean. Furthermore, applying the precautionary principle (Jordan and O’Riordan 2004) suggests that the greater uncertainty in outcome, the more conservative should be the management inputs (i.e., the higher the level of effort). Under a stochastic, risk-based model then, reclamation planning represents the balance between the probability of an undesirable outcome and the marginal improvement in outcome from an additional unit of investment. Figure 3, for example, shows a level of effort that generates an average response of 50%, with approximately equal outcomes above or below a desired threshold. The mean response can be increased and the probability of an undesirable outcome decreased with a further increase in effort.

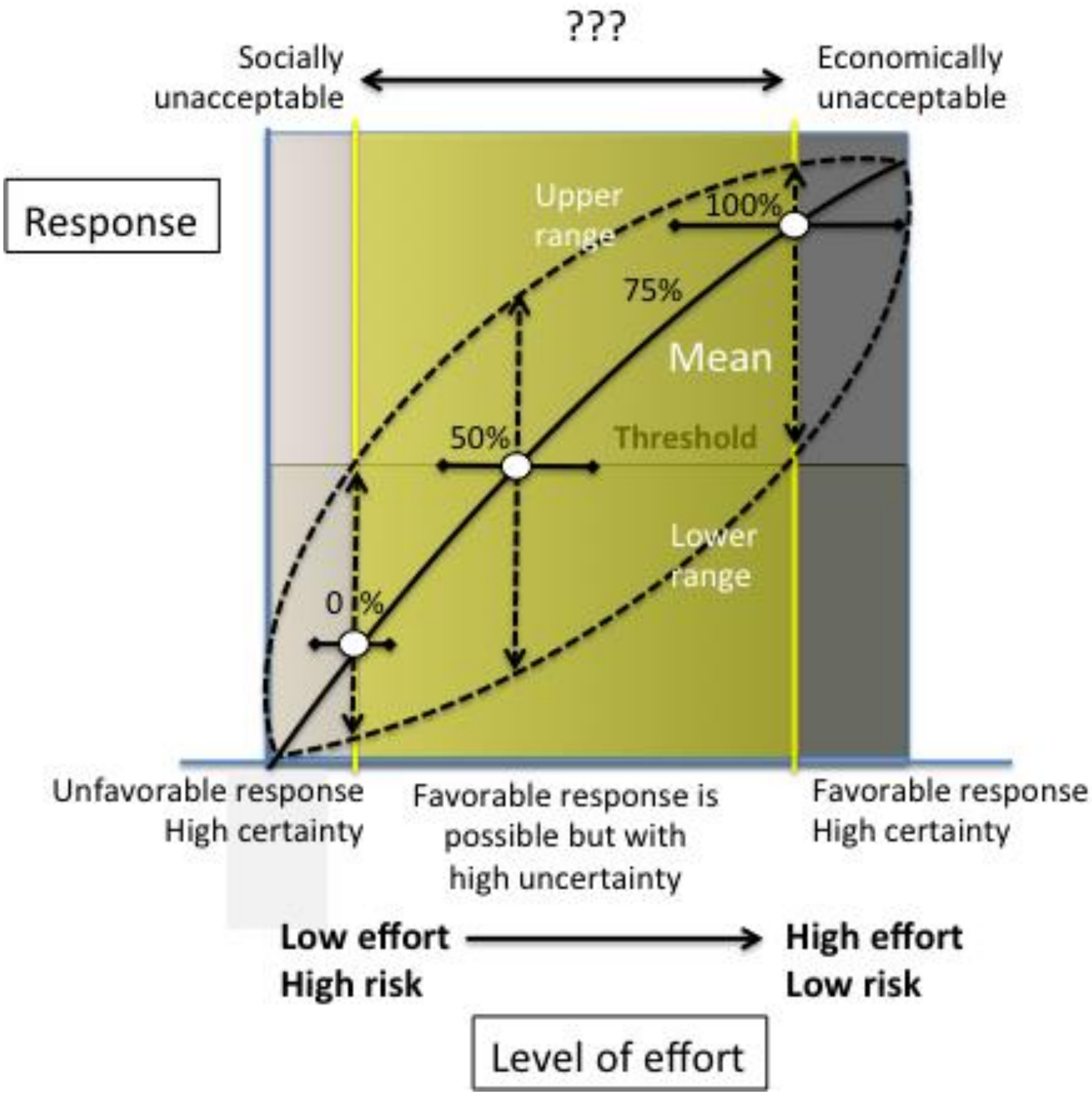


Figure 3. A conceptual risk-reward model for reclamation planning.
The level of effort expended in reclamation has a direct impact on the mean response (solid black line). Open circles denote individual mean responses with associated percentages.
Variability in the effort level (horizontal lines associated with a given mean response) can be a direct result of management decisions, or because ‘effort’ is degraded over time, as a consequence of climate-driven mortality events, for example. Vertical dashed arrows denote the upper and lower response ranges associated with a given variation in the level of effort. These are derived from response functions, as exemplified for crown closure in Figure 2.
At a very low level of effort, positive variation improves outcome proportionally more than if the variance is in the negative direction; the opposite occurs at a very high effort level. The risk of not achieving the threshold level with low effort is high and not socially acceptable, whereas very high effort has a low risk of not exceeding but the threshold but is economically impractical. Most reclamation planning decisions reside within the area of highest uncertainty (yellow area).

3 SPATIAL AND TEMPORAL UNCERTAINTY

3.1 Time: Present Versus Future Uncertainty

One consideration in accounting for climate change is timescale. Over the next several decades, uncertainty in climate predictions will be predominantly a consequence of natural climatic variability. The ‘noise’ generated from this year-to-year variation will effectively mask any underlying climate change trend. Model output indicates that it will be at least 30 years before differences among emissions scenarios have an appreciable impact on the climate. The relative effect increases significantly thereafter, which means the climate change signal will become clearer and more predominant during the latter decades of this century (IPCC 2007). This has implications for reclamation planning, as follows.

First, prescriptions that appear suitable for establishing stands under current climate conditions may prove inadequate in the future. Growing season moisture stress is not uncommon in the southern boreal (Hogg 1994, Hogg and Hurdle 1995) or the Fort McMurray region, particularly on reclaimed materials (Carey and Petrone 2014). As the climate warms (Barrow and Yu 2005), survival rates could decline accordingly if this leads to drier conditions in the growing season. White spruce regeneration, for example, is particularly sensitive to available moisture (Hogg and Swartz 2008), as is aspen regeneration from seed (Peterson and Peterson 1992). Mitigating these impacts and maintaining establishment success may require planting larger seedlings and at higher densities, and using drought-tolerant provenances and species (see, for example, Gray et al. 2011, Man et al. 2014).

A second question is the extent to which short-term trends are a reliable index of future performance, particularly as climate change becomes more predominant later in the century. A priority for mine operators is to secure a reclamation certificate for lands that have been reclaimed successfully. For practical purposes, reclamation success is evaluated within the first several decades using a series of metrics (Alberta Environment 2010). These are utilized as proxy measures of future performance (Figure 2A). There is evidence that mortality among mature aspen stands in the southern boreal region is the result of moisture stress (Hogg et al. 2008). There is also an indication that this trend is becoming widespread across western North America in many tree species (van Mantgem et al. 2009). Conversely, since NPP in northern forests is temperature-limited, a warming climate could improve growth over the long term, particularly if there is a CO_2 fertilization effect (see Peng and Apps 1999). This would at least partly offset lower tree densities from elevated mortality.

3.2 Space: Uncertainty at the Stand and Landscape Level

A forest stand is ‘a community of trees sufficiently uniform in species, age, arrangement or condition as to be distinguishable as a group in the forest or other growth in the area’ (Alberta Environment and Sustainable Resource Development 2012). As a physically discrete entity, stands are the principle focus of forest management practice. Hence, from a reclamation perspective, stand-level outcomes are a necessary prerequisite to successful reclamation, particularly if performance is focused on utilitarian metrics (merchantable volume, for example).

Evidence suggests, however, that for the public at large, reclaimed areas are more likely to be evaluated in terms of their amenities, such as scenic beauty, 'naturalness', and recreational value (Tahvanainen et al. 2001) – landscape-level attributes. These assessments are made largely on visual cues (Ribe 1989). Preferences typically favour forested areas interspersed with small openings (Bradshaw 1992, Paquet and Belanger 1997). Large open areas are viewed negatively, particularly if they are colonized by non-native species. Human preferences then are for moderate levels of habitat fragmentation (small open patches) and high connectivity, attributes that are also positively correlated to biodiversity (Fahrig 2003).

The boreal mixedwood landscape has been characterized as a 'mosaic' of stands of differing age and species composition (Weir et al. 2000). Hence, spatial heterogeneity on reclaimed landscapes is a desirable condition and should thus constitute a specific objective in reclamation planning. At least part of this objective will be realized indirectly by virtue of the fact reclamation occurs progressively. This will ensure heterogeneity among stand ages. A second option for creating heterogeneity is to 'plan for failure' (PFF). Under a PFF strategy, stands might be established under a relatively uniform set of prescriptions (at least as uniform as is practical) designed to achieve a highly desired end land-use; commercial forest, for example. As a consequence of random climatic events, stands are expected to vary in their developmental trajectories because of differences in, for example, age, landscape position, and species composition. A proportion of stands will therefore transition to a different end land-use than originally intended. This variation constitutes the basis on which the desired level of heterogeneity is created. The advantage of the PFF approach is that it simplifies the planning process because prescriptions are relatively uniform and there is no requirement for subsequent intervention if stand trajectories do begin to change. Lack of sufficient resources (capping materials, for example), however, could limit its application. One concern is the uncertainty in outcomes and the fact that success is evaluated *ex poste* (i.e., after the fact). If failure rates are well above or below expectations, this approach could serve to reduce landscape heterogeneity. As discussed below, models could provide a means for bounding the level of uncertainty.

Another option is to actively manage for landscape diversity by varying capping and planting prescriptions on a stand-by-stand basis. An area deemed ready for reclamation would thus be designated with respect to a specific end land-use and the appropriate prescriptions then applied. This approach adds complexity to the decision-making process but it has the advantage that outcomes are specified *ex ante* (i.e., before the fact) and so long-term objectives are clearly articulated at the time a site is reclaimed. Periodic interventions may also be required if stand development trajectories deviate significantly from the minimum necessary to achieve the desired end land-use.

Changes in the disturbance regime could render moot concerns around uncertainties in development trajectories[2]. In British Columbia, for example, the Mountain Pine Beetle (*Dendroctonus ponderosae*), epidemic is estimated to have killed Lodgepole pine trees across an area exceeding 5 million ha, and by 2017 almost three quarters of a billion m^3 of commercially valuable pine will have been lost (British Columbia Ministry of Forests 2014). One causal factor in the epidemic is a warming climate. Lack of deep cold in winter (less than -40 °C) has all but eliminated the high overwinter mortality rates necessary to keep populations in check (Carroll et al. 2003). The beetle is now established in both Lodgepole and jack pine stands in Alberta and is spreading towards the Fort McMurray region. This suggests avoiding pine as a dominant regenerative species to reduce risk of creating susceptible stands. Increases in forest fire frequency and intensity are another by-product of warming temperatures (Gillett et al. 2004). Reclaimed landscapes may thus be at increasing risk of catastrophic fire than indicated from the historical fire regime. Efforts at 'fire-proofing' landscapes include minimizing the coniferous component in favour of deciduous species, increasing landscape stand heterogeneity, thinning overly dense stands, and creating open areas to act as natural firebreaks. Since these options are not given explicit consideration in reclamation planning, changes in the risk of disturbance by insect and fire add more uncertainty to the assumption that current practices will be suitable for achieving long-term objectives.

4 ASSESSING PROBABLE OUTCOMES

As noted in previous sections, a fundamental challenge to assessing current best management practices within the context of climate change is the questionable utility of relying on historical practices for guidance. Nevertheless, the success of a particular reclamation prescription in meeting long-term objectives can, in principle, be assessed empirically. With sufficient replication (i.e., when enough stands have been reclaimed) it would then possible to calculate the probability of achieving a desired outcome. Comparing these probabilities, as per Figure 3, can provide a reasonable measure of the relative utility of alternative procedures and practices, given uncertainties introduced by climate change. In practice, however, many years must elapse before a reclaimed stand has developed sufficiently that a given prescription can be evaluated definitively. This also means that obtaining sufficient replicates or 'testing' alternative prescriptions will be problematic, especially if currently accepted reclamation practices are subject to change. A changing climate regime introduces additional uncertainty because future conditions will differ from those in the present. Modeling of ecosystem development is perhaps the only practical approach to resolving to this dilemma.

There have been two basic approaches to predictive modelling of ecosystem response to a changing climate: empirical (statistical)- and process-based models.

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[2] For further insight into this topic, see: 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 http://hdl.handle.net/10402/era.30360
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Climate envelope models are an example of the statistical approach. They rely on detailed analyses of historical climate data collected from a species' observed range. Deviations from climate normals are calculated for future climate scenarios and then used to project changes in species distributions (see, for example, Crookston et al. 2010, Gray 2011, Monserud et al. 2008, Roberts 2013). This approach could have some merit in reclamation planning in terms of assessing the suitability of current versus alternative species for planting though typically, these models are applied at regional scales. Another key limitation is that if the future climate exceeds the historical range of variation then applications of the model are beyond the scope of its statistical foundations.

State and transition models (STSMs) are another application of the empirical approach[3]. STSMs characterize a landscape according to a set of vegetation states (for example, age class, species composition, volume). Each parcel of land is assigned to a particular state at any given point in time with transitions and their associated probabilities that move a parcel from one state to another. STSMs have been applied across a wide range of landscapes, ecological systems and management problems (Daniel and Frid 2012). This includes the mineable oil sands of Alberta where an STSM has been used to evaluate reclamation planning alternatives at a landscape scale (Frid and Daniel 2012). Ideally, STSMs should be parameterized empirically, based on observations of past vegetation transitions in conjunction with stand level indicators of changes in ecosystem structure and function. As noted above, climate change renders this problematic because historical transitions and their probabilities will likely not be maintained. A practical approach to resolving these issues is to apply models that can make quantitative predictions of ecosystem development under future climate conditions, and then use the output to derive a new set of transitions. This approach is detailed below.

The second category of predictive modeling is process-based models. These models employ physiological and physical principles in conjunction with simulated edaphic conditions to project forest development and productivity under a changing climate. They vary widely in their complexity and application, ranging from comprehensive, research-oriented ecosystem models (e.g., Ecosys[4], Grant et al. 2006) to less complex, management-oriented models such as the CENTURY[5] (Peng and Apps), CABALA[6] (Battaglia et al. 2004) and 3PG[7] (Landsberg and Waring 1997). The more complex models can be difficult to calibrate because they usually comprise many site- and species-specific parameters, which can necessitate expensive, multi-year field research programs to support their application (e.g., Battaglia et al. 2004). Highly simplified process models may have lower calibration requirements but they often cannot adequately address the complexity of forest management in the face of climate change.

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[3] See http://www.blm.gov/wo/st/en/prog/more/soil2/soil2/model.html

[4] See http://www.rr.ualberta.ca/en/Research/EcosysModellingProject.aspx

[5] See http://www.nrel.colostate.edu/projects/century/

[6] See http://www.csiro.au/Organisation-Structure/Divisions/Ecosystem-Sciences/CABALA.aspx

[7] See http://www.csiro.au/Outcomes/Environment/Australian-Landscapes/3PGProductivity.aspx

A compromise approach is embodied in ‘hybrid’ process-based models, in which empirical data are used to ‘self-calibrate’ at least some of the algorithm parameters associated with ecosystem processes (see Kimmins et al. 2010). This makes it possible to retain adequate model complexity while minimizing the calibration load (Girardin et al. 2008). In terms of using these models to inform planning decision in the oil sands, prerequisites include an ability to address the operational realities of soils placement (peat-based capping material and variable placement depths), and that sites are established *de novo*, i.e., with no prior vegetation history.

Welham and his colleagues are applying a methodology for deriving probability outcomes for reclamation planning using the FORECAST Climate[8] model and an STSM (see Acknowledgements). The process-based forest growth model FORECAST[9] (Kimmins et al. 1999) has been applied to oil sands mine reclamation for almost 15 years. Its extension, FORECAST Climate (Seely et al. 2015) was developed to explore the impacts of climate and climate change on forest growth and development. FORECAST Climate will be used to project vegetation development for a given reclamation land unit (dry, moist rich, moist poor, wet rich, and wet poor; see Frid and Daniel 2012) subject to current and alternative management options, disturbance regimes, and two climate change scenarios (Table 1).

To derive potential vegetation transition pathways, model output (i.e., vegetation development) is classified into discrete ‘states’ using predefined attribute thresholds. Example indicators for these thresholds include crown closure, site index, biomass and volume accumulation, and species composition. FORECAST Climate simulations are conducted with random variation in mortality and various site features in conjunction with interannual variability in climate conditions, the latter of which includes no climate change (i.e., the historical climate regime) and climate change. The probabilities associated with each state transition will then be derived from these runs (see Figure 4).

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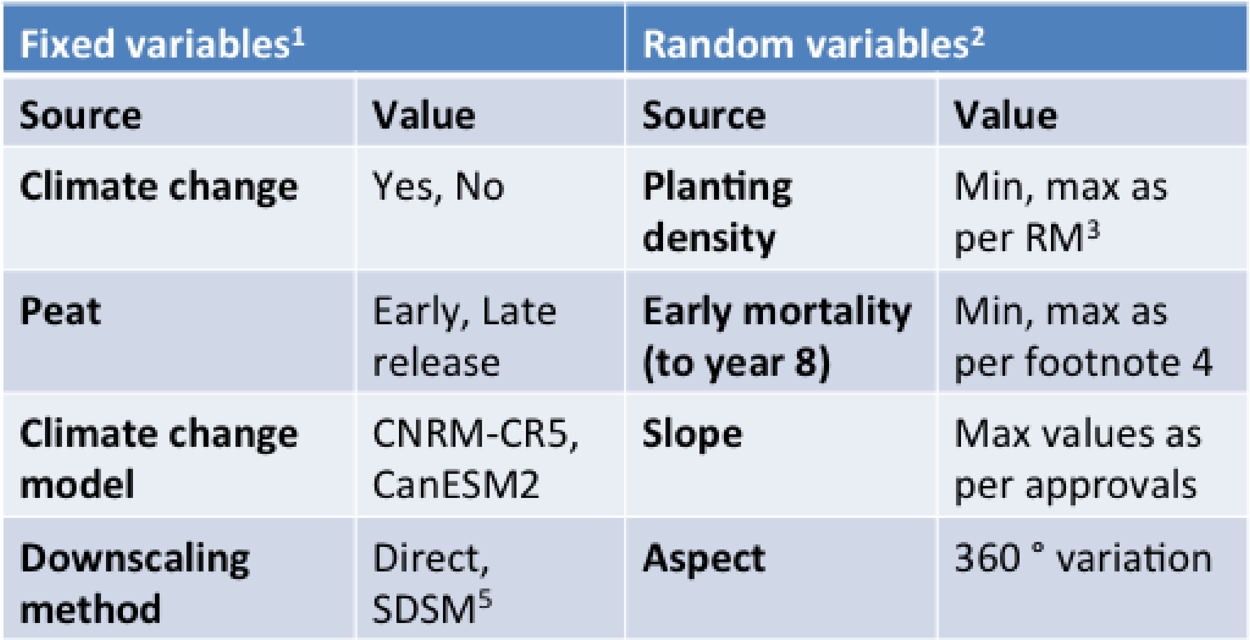
[8] See http://web.forestry.ubc.ca/ecomodels//moddev/forecast%20climate/forecast%20climate.htm

[9] See http://web.forestry.ubc.ca/ecomodels//moddev/forecast/forecast.htm

Table 1. Two sources of uncertainty, fixed variables and random variables, used in FORECAST Climate simulations.



Fixed variables[1]		Random variables[2]	
Source	**Value**	**Source**	**Value**
Climate change	Yes, No	**Planting density**	Min, max as per RM[3]
Peat	Early, Late release	**Early mortality (to year 8)**	Min, max as per footnote 4
Climate change model	CNRM-CR5, CanESM2	**Slope**	Max values as per approvals
Downscaling method	Direct, SDSM[5]	**Aspect**	360 ° variation

[1] Variable whose value is known at the beginning of a simulation.

[2] Variable whose value is drawn from a random, bounded distribution.

[3] Revegetation Manual (Alberta Environment 2010)

[4] Associated Strategic Consulting Experts Inc., 2011.

[5] Statistical Down Scaling Model (SDSM)[10]: used to increase variation in climate variables over time.

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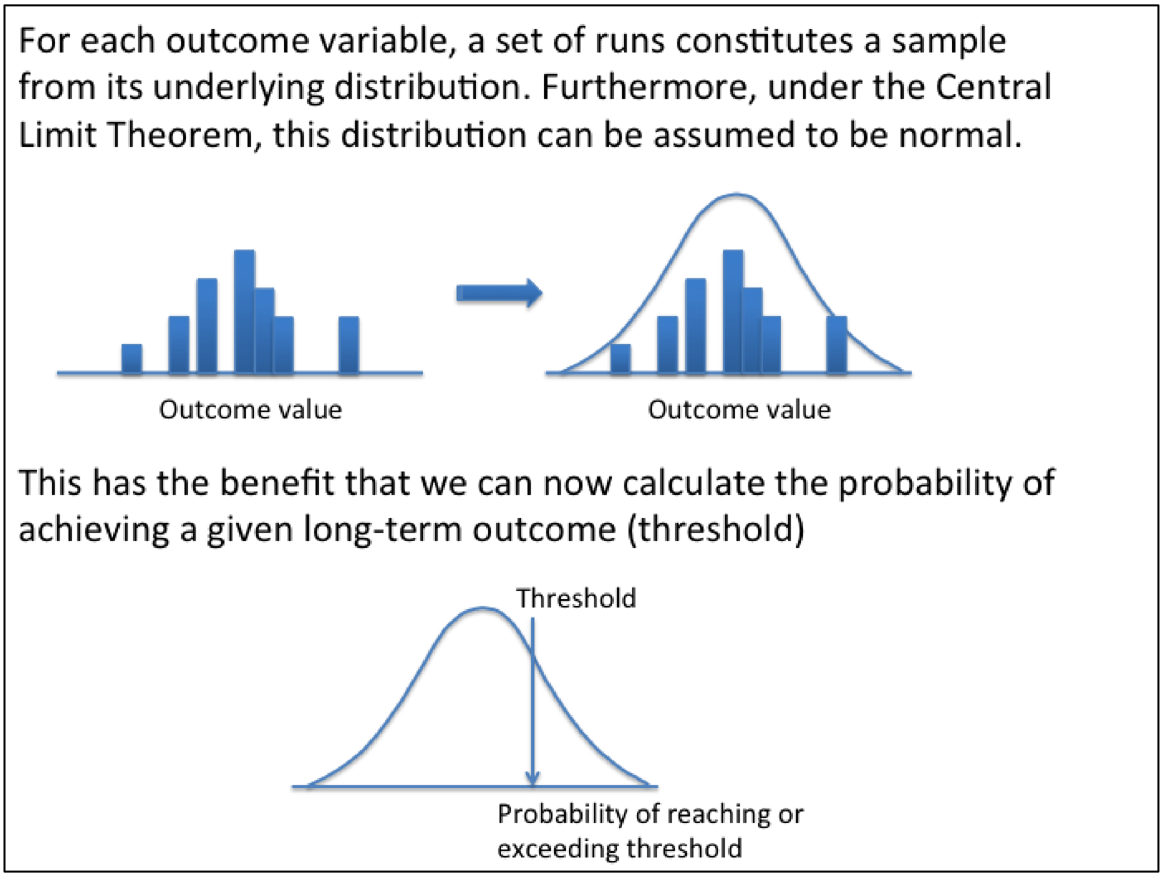
[10] See http://unfccc.int/adaptation/nairobi_work_programme/knowledge_resources_and_publications/items/5487.php



For each outcome variable, a set of runs constitutes a sample from its underlying distribution. Furthermore, under the Central Limit Theorem, this distribution can be assumed to be normal.

This has the benefit that we can now calculate the probability of achieving a given long-term outcome (threshold)

Figure 4. A schematic representation of how probabilities are calculated from FORECAST Climate for use in the STSM.
A set of outcomes (height growth or volume, for example) is generated from FORECAST Climate and used to create a normal distribution. From this distribution, the probability of exceeding any given threshold value can be calculated.

The STSM is first calibrated with inventory information and current reclaimed sites classified into land units (LUs) and land unit phases (vegetation types). This constitutes the starting condition. Environmental Impact Assessment documents and the mine reclamation and closure plans are used to construct the anticipated pattern of progressive reclamation (see Pickard et al. 2013, Welham 2010, Welham and Seely 2011). The STSM then simulates vegetation development (states) for a given LU over time. By implementing a Monte Carlo experiment (i.e., repeated iterations through the STSM) in conjunction with the transition probabilities from FORECAST Climate, uncertainties in outcome for a given reclamation practice will be assessed as a consequence of climate change.

Model output will permit stakeholders and regulators to evaluate the efficacy of current and alternative adaptation strategies with respect to mitigating risk of undesirable outcomes. In addition, the STSM will be provided with the capability for geospatial representation of each land unit and land unit phase. This functionality will aid mine operators in meeting approvals conditions regarding integration across lease boundaries and with undisturbed areas. The tool will also be useful for wildlife habitat planning and assessment of reclamation performance with respect to re-establishing wildlife habitat (both of which have a strong spatial component; see Welham 2010).

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6 GLOSSARY

6.1 Terms

Crown Closure

The extent to which the crowns of trees touch and effectively block sunlight from reaching the forest floor. Crown closure is expressed as a percentage or proportion.

Deterministic Model

Model output is fully determined by the parameter values and the initial conditions.

Landscape

Interacting geographic areas that are bounded by physical features and that contain similar patterns of watersheds and vegetation cover. Ecological landscapes have no fixed size.

Land Unit

A tract of land that can be identified and distinguished using its basic ecological features. Example features includes moisture status (dry, moist, or rich) and/or nutrient regime (poor, medium, and rich).

Plan for Failure Strategy

A policy that takes into account the likelihood of variable outcomes, some of which will be below threshold targets. This range in outcomes ensures diversity in long-term objectives.

Stand

A community of trees sufficiently uniform in species composition, age, arrangement, and condition to be distinguishable as a group from the forest or other growth on an adjoining area. Typically, stands constitute a silviculture or management entity.

State

A vegetation community that can be identified and distinguished from other communities in accordance with its structures (e.g., dominant species, functional groups, and surface soil conditions), and how those structures might control feedback mechanisms and ecological processes.

Stochastic model

Possesses inherent randomness in its initial conditions and/or parameter values. As a result, only the probability of a given outcome can be predicted.

Trajectory

The pattern or sequence of states.

Transition

A change from one state to another.

6.2 Acronyms

CC	Crown Closure
DST	Decision Support Tool
GHG	Greenhouse Gases
LU	Land Unit
NPP	Net Primary Production
OSRIN	Oil Sands Research and Information Network
PFF	Plan For Failure
SDSM	Statistical Down Scaling Model
SEE	School of Energy and the Environment
STSM	State-and-Transition Simulation Model

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