Oil Sands Terrestrial Habitat and Risk Modelling for Disturbance and Reclamation: The Impact of Climate Change on Tree Regeneration and Productivity – Phase III Report

C. Welham and B. Seely

University of British Columbia, Vancouver, British Columbia

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Oil Sands Research and Information Network

Oil Sands Research and Information Network

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REPORT SUMMARY

The overall objective of this project is to develop a framework that integrates risk management and strategic decision-making to evaluate the impact of disturbance (natural and industrial) on ecosystem products and services, and on habitat availability for terrestrial species in Alberta's Lower Athabasca planning region. This also includes an evaluation of conservation, and reclamation activities associated with oil sands development both at the lease and regional levels.

The project has been conducted in phases. Each phase is sequential such that its results and conclusions represented the foundation for subsequent work. This report summarizes activities conducted as part of Phase III, consisting of the following: (1) Model projections of tree regeneration under climate change on actual oil sands reclamation materials, and (2) A comprehensive model analysis of the risks to ecosystem productivity from climate change as a consequence of the impact of moisture stress on tree mortality.

Model projections of plant regeneration under climate change on actual oil sands reclamation materials

Six climate change scenarios for Alberta were selected that encompassed a range of predictions in future temperature and precipitation change. The tree and climate assessment (TACA) model was calibrated for reclaimed sites that varied in their soil moisture regimes (from xeric to subhygric) and three natural sites, High Level (subxeric), Calling Lake (mesic), and Fort Chipewyan (subhygric). TACA was used to predict regeneration probabilities on these sites for jack pine, aspen, and white spruce, in conjunction with the climate change scenarios.

A comparison between the natural sites and their corresponding moisture regimes on reclaimed sites showed little quantitative difference in predicted regeneration for High Level. Regeneration probabilities for Calling Lake and Fort Chipewyan, however, were lower than the corresponding moisture regimes on reclaimed sites (mesic and subhygric, respectively). The differences in the Calling Lake and Fort Chipewyan sites are largely a consequence of the fact that percolation rates were higher on natural versus the reclaimed sites. These results highlight the importance of assessing soil moisture regime using a variety of metrics.

Across climate periods, regeneration in this northern region was generally improved in jack pine and aspen because of the warming temperatures and in some scenarios, increases in annual precipitation, predicted under climate change. This was particularly the case in the wetter moisture regimes (submesic to subhygric) than the subxeric and xeric regimes, probably due to increases in growing season moisture deficits in the latter. Aspen regeneration from suckering had substantially greater predicted success than aspen regenerated from seed. Predicted trends in white spruce regeneration were in sharp contrast to the other species. Spruce regeneration was reduced substantially in future periods to the point where it was predicted to be less than 20% in subxeric and xeric moisture regimes. These results indicate that from a reclamation perspective, the impact of climate change on regeneration requires careful consideration of the tree species and its associated moisture regime.

Soil moisture regime generated pronounced differences in regeneration probabilities both within a given future time period, and across periods. As might be expected, regeneration was highest

in the wettest moisture regime and declined as the moisture regime became drier. However, the difference between moisture regimes within a given time period also increased over time for all species. From the perspective of reclamation outcomes, these results suggest soil prescriptions should be developed and/or applied which generate moisture regimes that are submesic and wetter. Drier regimes (subxeric and xeric) appear to introduce a substantially greater average risk that revegetation success in a future climate may be compromised through regeneration failure.

How well might current reclamation prescriptions be expected to perform under climate change with respect to regeneration success? Overall, results suggest that no single set of prescriptions will be adequate to maintain the current suite of tree species common to the region. Nevertheless, current one-layer prescriptions seem adequate for maintaining pine and aspen regeneration, at least on average. Practices governing spruce, in contrast, should transition over the next several decades towards an emphasis on constructing two-layer prescriptions only, in an effort to minimize the risk of inadequate regeneration. This has important implications for mass balance calculations associated with soil amendment materials. In short, drier sites should focus on pine and possible aspen regeneration, and spruce on wetter sites.

For a risk management perspective, reclamation practices that generate the two wettest moisture regimes (mesic and subhygric) are most likely to result in successful outcomes, at least through the 2050s. Drier moisture regimes can have lower regeneration probabilities but results were often highly inconsistent across the climate scenarios; constructing covers that generate drier moisture regimes thus entails considerably more risk of inadequate regeneration. Although regeneration was high in the 2080s, in many moisture regimes uncertainty in model predictions was also high. However, because of this extended time frame, modifying current reclamation practices or planting prescriptions to mitigate this risk is not warranted. Taken together, results emphasize the point that the climate will continue to change and highlight the necessity for ongoing investment in this type of analysis to facilitate the process of continuous learning that can form the basis for adaptive management.

Analysis of risks to ecosystem productivity from climate change using FORECAST Climate

Drought is anticipated to be an increasingly limiting factor for plant productivity and survival in the Fort McMurray region. Regional climate data indicate that this trend has already begun with patterns of growing season moisture deficits increasing since the 1960s.

A new drought mortality function was developed and implemented within FORECAST Climate. In contrast to the threshold mortality approach employed in previous analyses, the new continuous function simulates drought mortality using a two-year running average of a species-specific moisture stress as a predictor of annual mortality. The 2-year running average is designed to capture the compounding effect of consecutive dry years. The amplitude of the function curve was fitted to historical climate data for each species so that mortality rates were consistent with empirical observations of actual mortality events. Two different mortality curves (low and high) were simulated for each tree species to explore the sensitivity of the model to assumptions regarding tree susceptibility to drought stress. To simulate the effects of a changing climate, five climate-change and associated emissions scenarios were utilized, and one scenario representing the historical climate regime. Simulations were conducted for ecosites dominated by jack pine (ecosite a1), aspen (d1), and white spruce (d3).

Jack pine showed very little mortality under the historical climate regime at either index of drought sensitivity. In the case of aspen (ecosite d1) and spruce (ecosite d3), historical drought-related mortality events were not uncommon in the simulations, consistent with empirical data.

Projections of future climate conditions generated mixed results in terms of mortality, depending on the emission scenario. With the exception of A1FI, all other emission scenarios triggered mortality below historical conditions at various points in the simulation. Given that primary productivity at high latitudes is temperature limited, a warming climate thus has the potential to improve survival under some circumstances, though not necessarily on sites where drought is already problematic. Within a given species, the highest mortality almost always occurred under the A1FI emissions scenario. Though A1FI was considered a pessimistic outcome in terms of CO_2 emissions, current evidence indicates that, in fact, it may be close to reality.

Pine and spruce appear generally robust to drought conditions at least over the next several decades, regardless of the climate regime. Mortality tended to increase thereafter as the simulation years got longer (i.e., later in the century). In absolute terms, pine is projected to have the lowest overall drought-related mortality (the exception being mortality under the A1FI emission scenario) while spruce is projected to have the highest mortality, particularly late in the century. Aspen showed a small increase in mortality over time beginning in the first decade of the simulations.

The Climate Response Index (CRI) is a metric calculated in FORECAST Climate that integrates the impact of temperature and precipitation. Similarly, the decomposition response index (DRI) links decomposition (i.e., nutrient availability) to temperature and moisture. Both indices thus serve as proxy measures of climate-related growth conditions. The A1FI scenario, by example, always generated higher CRI and DRI values than occur under historical climate conditions. Nevertheless, assumptions regarding tree sensitivity to drought stress had a significant impact on volume production and its relation to climate change. When the mortality rate was low (i.e., species were robust to moisture stress), volume production under climate change always exceeded that projected under the historical climate regime. If species are less tolerant of moisture stress (i.e., the mortality rate function was high) climate change will have a negative impact on stand-level productivity later in the century, though how much depends on the particular species and a given emissions scenario.

Significant reductions in productive capacity from climate-driven mortality threaten to destabilize ecosystems beyond their resilient capacity. One feature that would serve to promote resilience by avoiding drought stress is to ensure the rooting zone possesses adequate available water holding capacity. This can be accomplished by ensuring capping materials have higher organic matter content, are not predominantly coarse textured, and of sufficient depth. Layering of capping materials to generate textural breaks also serves to increase moisture storage, at least temporarily. Another important feature in creating resilience is to properly match tree species to their edatopic position. Aspen, and particularly spruce, occupy wetter positions on the edatopic grid. For the most part, these species are more prone to drought than pine. It is important then to ensure they are not planted on sites that may become marginal in terms of available moisture. In that respect, another consideration is to actively modify planting prescriptions in anticipation of a drier climate. Conceptually, this approach is based on the assumption a given soil moisture regime will for all intents and purposes transition to a drier edatopic position with further climate warming.

In Europe, mitigative activities against climate change at the stand level are focusing on the regeneration phase. This is because a well-established plant population will have better prospects for surviving the vagaries of future (and largely uncertain) climate conditions and the fact little can be done to affect survival in stands that are mature today. Hence, one approach is to increase the genetic or species diversity in seeded and planted stands. This can be accomplished with traditional tree-breeding programs (termed provenance trials) though molecular genetics techniques have been developed that significantly reduce the time and resources needed for the selection process. Other possible silvicultural measures to promote establishment and maintenance of desired communities include moving up the planting season to take advantage of earlier spring conditions, using containerized stock to reduce drought risk, enhancing drought tolerance by employing seedlings with higher root:shoot ratios, and reduced spacing to increase recovery after dry periods.

Quantitative models, such as TACA and FORECAST Climate, can project forest responses and the goods and services those forests provide to a range of future climate change scenarios. Predictions made using these climate-based models need to inform best management practices and can be coupled to the continuous learning that forms the basis of an adaptive management process, thereby reducing the uncertainty associated with reclamation decisions.

The report closes with conclusions and associated recommendations, and a final section describing potential next steps.

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1 INTRODUCTION

The overall objective of this project is to develop a framework that integrates risk management and strategic decision-making to evaluate the impact of disturbance (natural and industrial) on ecosystem products and services, and on habitat availability for terrestrial species in Alberta's Lower Athabasca planning region. This also includes an evaluation of conservation, and reclamation activities associated with oil sands development both at the lease and regional levels. A comprehensive overview of the project is provided in the document entitled Oil Sands Terrestrial Habitat and Risk Modelling for Disturbance and Reclamation, submitted to the Oil Sands Environmental Management Division, of Alberta Environment.

The project was conceived as utilizing a phased approach. Each phase is sequential such that its results and conclusions represent the foundation for subsequent work.

Phase I work consisted of three principal activities described in detail in three linked reports under the broad title Oil Sands Terrestrial Habitat and Risk Modelling for Disturbance and Reclamation Phase I[1]. The activities included:

1. A dendrochronology study that examined the relationship between climate and tree growth (specifically ring width) for four species (white spruce – *Picea glauca*, black spruce *Picea mariana*, jack pine – *Pinus banksiana*, and trembling aspen – *Populus tremuloides*) in the sub-boreal forests of western Canada (Alberta and Saskatchewan).

   a. A habitat suitability analysis for ten boreal forest wildlife species (moose, black bear, snowshoe hare, lynx, red-backed vole, fisher, Cape May warbler, ruffed grouse, pileated woodpecker, and northern goshawk) in natural forests and within reclamation plans developed as part of the Kearl Lake mine[2]. Input values for each index were derived from output generated from the ecosystem simulation model, FORECAST.

   b. A risk analysis of the potential development of water stress in young reclamation plantations consisting of white spruce, trembling aspen, and jack pine established on different ecosites as a function of soil texture and slope position.

In Phase II, the principal objective was an evaluation of the impact of climate and climate change on reclamation success, as compared to the base case analysis (no climate-related impacts) conducted in Phase I[3]. The potential effect of different climate change scenarios on growth and

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[1] See Welham, C., 2010. *Oil Sands Terrestrial Habitat and Risk Modeling for Disturbance and Reclamation – Phase I Report*. OSRIN Report No. TR-8. 109 pp.

[2] Imperial Oil Resources Ventures Limited Kearl Oil Sands Mine Project - http://www.imperialoil.ca/Canada-English/operations_sands_kearl.aspx

[3] See Welham, C. and B. Seely, 2011. Oil Sands Terrestrial Habitat and Risk Modelling for Disturbance and Reclamation – Phase II Report. Oil Sands Research and Information Network, University of Alberta, School of

mortality in reclamation areas was projected using the FORECAST Climate model and associated modelling tools to evaluate their combined impacts on overall ecosystem development in a risk assessment context. As in Phase I, the Kearl Lake mine development plan was used as the test case.

Activities in Phase II were scheduled to occur in five parts (see Figure 1). The basic approach was to explore climate impacts on key components of the reclamation 'cycle'. In Part 1, a sapwood growth submodel was used to project annual stemwood increment for jack pine, aspen, and white spruce on sites representative of the Kearl Lake reclamation landscape using daily historical climate data from the Fort McMurray region. These sapwood increment projections were compared against selected tree ring chronologies derived from the Phase I work. This exercise constituted a means for 'testing' the hypothesized relationships between climate and ring growth and for developing a clearer understanding of the interaction between phenology (when carbohydrate production switches between growth and storage) and climate. It also provided a method for calibrating FORECAST Climate's projections of net primary productivity in terms of patterns in ring growth. In Part 2, five greenhouse gas emission scenarios used by Barrow and Yu (2005) in their climate change projections for Alberta were compiled and downscaled for use in subsequent analyses. The Tree and Climate Assessment (TACA) model was employed in Part 3 to evaluate how regeneration success on natural ecosites might be affected by climate change (further details on TACA are provided below). The focus of Part 4 was to evaluate future ecosystem development using the FORECAST Climate model within the context of the climate change scenarios derived in Part 2. This exercise projected the long-term productivity and development of structural and ecosystem attributes for different ecosites within the Kearl Lake mine reclamation area.

Due to funding limitations and logistical issues associated with the incorporation of climate change variables, not all Phase II objectives were completed.

Energy and the Environment, Edmonton, Alberta. OSRIN Report No. TR-15. 93 pp. http://hdl.handle.net/10402/era.24547

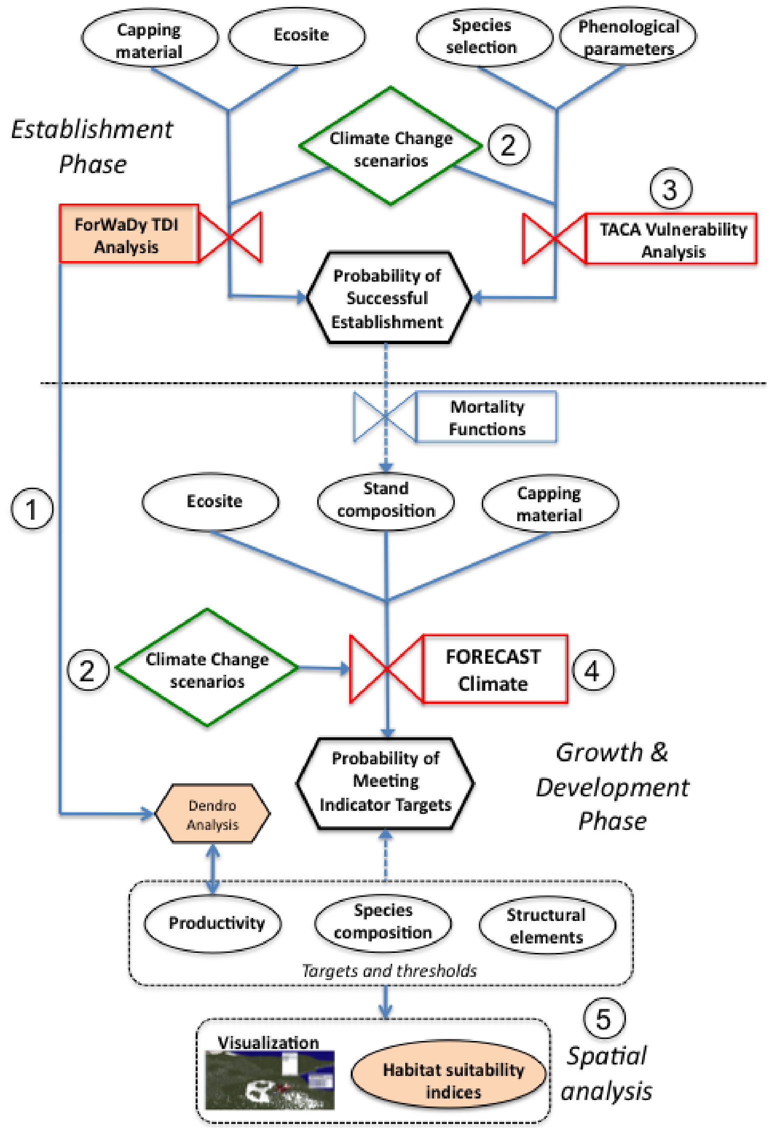

Figure 1. Schematic illustration of Phase II activities.
In Part 1, FORECAST Climate was evaluated against regional tree ring data sets. Climate change projections are derived and downscaled in Part 2. These projections were then used as input to the TACA regeneration model and the ForWaDy water balance models (Part 3) and to the FORECAST Climate model (Part 4). In Part 5 (future work), habitat suitability indices will be projected for the Kearl Lake reclaimed landscape when spatially explicit metrics are included. The spatial and temporal trends in each index will be the portrayed through the creation of 3-dimensional landscape images that can be viewed and explored in a web-based interface (see text for further details).

Two tasks that were not completed constitute the Phase III activities reported here:

1. Projecting tree regeneration under climate change on actual oil sands reclamation materials. As noted above, in Phase II Part 3, the TACA model was used to evaluate how regeneration success might be affected by climate change on natural ecosites. This activity was thus designed as a direct comparison between reclaimed and natural soils because of differences in their material composition. In the interim, a new version of TACA was released that included a series of important modifications. This rendered the intended comparison questionable since any discrepancies could have been a consequence of using different versions of TACA and/or differences in soil properties; it would thus have been difficult to discriminate between the two. We therefore re-ran the analysis for both the natural and the reclaimed soils with the updated model.
2. A comprehensive model analysis of the risks to ecosystem productivity from climate change as a consequence of the impact of moisture stress on tree mortality.

Additional tasks to be completed include the spatial analysis of indices of habitat suitability and the 3-dimensional visual representation of plantation development, both components of Part 5 (Figure 1). These were not included in the work described in this report.

2 PROJECTING PLANT REGENERATION UNDER CLIMATE CHANGE ON OIL SANDS RECLAMATION MATERIAL

2.1 Accounting for Model Improvements

In the Phase II work, regeneration probabilities were derived for three natural ecosites using the Tree and Climate Assessment model, TACA 2011. A brief description of TACA is provided in Appendix 1 (see also, Welham and Seely 2011). In the interim, several modifications were made to TACA to improve its performance (C. Nitschke[4], pers. comm.), with an accompanying version release (TACA GEM; Germination and Establishment Model). Changes to TACA are as follows.

2.1.1 *Conversion from Binary to Continuous Variables*

Formulae for two of the response variables (growing degree days and site-specific drought) were updated to generate continuous output (between 0 and 1) instead of binary output (0, 1). Minimum growing degree-day thresholds trigger bud burst whereas maximum thresholds set an upper limit beyond which regeneration is impeded. A drought index is calculated for each species; excessive drought triggers regeneration mortality.

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[4] Melbourne School of Land and Environment, Forest and Ecosystem Science, University of Melbourne, Melbourne, Australia (craign@unimelb.edu.au).

2.1.2 *Addition of Extreme Events*

This is a calculation of the potential impact of extreme climate events on species establishment, specifically mortality from killing frosts and drought events. Killing frosts occur when air temperature drops below a minimum species-specific threshold. Drought mortality is calculated based on the frequency with which a species-specific drought threshold is exceeded. If the threshold is exceeded more than 50% of the time over a 10-year period, mortality occurs. This calculation is additional to the negative impact of drought on regeneration that TACA calculates for a single climate-year.

A list of the calibration data used in TACA is provided in Appendix 2. Comparison of the two TACA versions suggests that the regeneration probabilities from the new version of the model are generally lower than those predicted by the old version (see Appendix 3). Hence, had the natural soils not also been re-run, this would have generated a bias in results.

2.2 An Additional Climate Scenario

The first step in simulating climate change is to select one or more emission scenarios because projections of future climate from a given global circulation model (GCM) are derived, in part, in relation to a particular emissions scenario. There are about 40 scenarios identified by the Intergovernmental Panel on Climate Change, each making different assumptions of future greenhouse gas pollution, land-use and other driving forces such as technological and economic development. Most scenarios include an increase in consumption of fossil fuels though some project lower levels of consumption by 2100, as compared to 1990 levels.

More than two-dozen GCMs have been developed to date. Different GCMs respond differently to the same emission scenario because, although some components are common to most or all models, they also each have different ways of characterizing other aspects of the climate system. Differences among the models are thus one of the larger sources of variability in generating climate data projections though no single model (or perhaps, emission scenario) can be considered as more plausible than another.

Using the Alberta Climate Model as a baseline, and a series of GCMs, Barrow and Yu (2005) simulated future climate scenarios for Alberta relative to the baseline period, projected for the 2020's, 2050's, and 2080's. From a large suite of emission and GCM scenario combinations, five scenarios were selected based on predicted variation in temperature and precipitation during the summer season. Four represented the more extreme changes in mean temperature and precipitation, and one represented median conditions. These were: NCAR-PCM A1B (cooler, wetter), CGCM2 B2(3) (cooler, drier), HadCM3 A2(a) (warmer, wetter), CCSRNIES A1FI (warmer, drier) and HadCM3 B2(b) (median)(see Welham and Seely 2011, Table 6). These climate scenarios were also used in Phase III. One additional climate scenario was also added that constitutes a more recent climate change projection relative to the Barrow and Yu scenarios. Adapted to the Fort McMurray region and based on the A2 emissions scenario, this climate scenario was derived from the average of a series of runs conducted as part of the IPCC Fourth Assessment Report (AR4; published in 2007) and obtained from the Pacific Climate Impact Consortium (PCICs) online regional analysis tool (http://pacificclimate.org/tools-and-data/regional-analysis-tool). The characteristics of this average A2 scenario were similar to the HadCM3 A2(a) scenario; towards the warmer end of the range with a small increase in growing season precipitation.

2.3 Soil Features

In general, the basic prescription for reclaiming oil sands materials involves the application of either a 'one-layer' or 'two-layer' soil replacement process (Alberta Environment 2010). In one-layer reclamation, peat is overstripped to include 25% to 50% by volume of mineral overburden. This peat:mineral mix amendment is then applied as a cover soil to a depth of 50 cm over the underlying material, either tailings sand or non-sodic/saline overburden. In two-layer operations, up to 1 m of sandy or clayey subsoil is placed over material deemed unsuitable for plant rooting (generally because of salinity issues). A 50 cm layer of peat:mineral mix is then used as the capping material. When sufficient material is available, a thin layer of forest floor (termed LFH) material may be added to the soil surface as a propagule source (see Alberta Environment 2010, for details).

One of the key factors manipulated through construction of a reclamation soil cover is available water holding capacity (AWHC), which can be considered as an index of the capacity of a soil to supply water to a developing plant community. Calculation of AWHC takes into account the depth, texture, and coarse fragment content of the cover material, as well as slope and aspect. Table 9 in the Land Capability Classification System manual (Alberta Environment 2006) shows the breakdown of soil moisture regimes (SMR) with respect to natural soils in the oil sands region (Table 1), as well as an adjusted AWHC for each moisture regime. The adjustment reflects the fact that layering and slope position are accounted for.

Table 1. Moisture regime classes from the LCCS.

Moisture Regime	Description	Idealized Slope Position[1]	Surface Organic Thickness (cm)	Water Table Depth (cm)	Primary Water Source	Common Texture[2]	Soil Drainage Class	Common Ecosites[3]	Adjusted AWHC[4] (mm 100 cm)	SMR Index and Subclass
Very xeric (1)	Water removed extremely rapidly in relation to supply; soil is moist for a negligible time following precipitation.	A – B All	< 3	>100	Precipitation	Very coarse (gravel – S) Shallow soil	Very rapid	n/a	<56[5] (40)	10X
Xeric (2)	Water removed very rapidly in relation to supply; soil is moist for brief periods following precipitation.	A – B All	< 3	>100	Precipitation	Coarse (S)	Very rapid to rapid	a	56 – 85 (70)	24X
Subxeric (3)	Water remover rapidly in relation to supply; soil is moist for short periods following precipitation.	B – C Variable	< 3	>100	Precipitation	Coarse to moderately coarse (LS – SL)	Rapid	a, b	86 – 115 (100)	38X
Submesic (4)	Water removed readily in relation to supply; water available for moderately short periods following precipitation.	B – C Variable	3 – 5	>100	Precipitation	Moderately coarse (SL)	Rapid to well	b, c, d	116 – 145 (130)	52
Mesic (5)	Water removed somewhat slowly in relation to supply; soil may remain moist for significant but sometimes short periods of the year; available soil water reflects climatic inputs.	C Variable	6 – 9	>100	Precipitation in moderate to fine-textured soil and limited seepage in coarse-textured soils	Medium (SiL – L) to fine (SCL – C) Few coarse fragments	Well to moderately well	c, d	146 – 175 (160)	66
Subhygric (6)[6]	Water removed slowly enough to keep the soil wet for a significant part of the growing season; some temporary seepage and possible mottling below 20 cm.	D Variable	10 – 40	May be < 100	Precipitation and seepage	Variable depending on seepage	Imperfect	e, g	Equivalent to > 175 (190)	80
Hygric (7a)[6]	Hygric aerated: Water removed slowly enough to keep the soil wet for most of the growing season; mottling present within 50 cm.	E – G	16 – 40	30-100	Permanent seepage; water table fluctuates often <100 cm	Variable depending on seepage	Poor	g, h, f	Wet	66
Hygric (7r)	Hygric reduced: Water removed slowly enough to keep the soil wet for most of the growing season; >50% gley within 50 cm.	E – G	16 – 40	30-100	Seepage; water table fluctuates often <100 cm	Variable depending on seepage	Poor	g, h, f	Wet	24W
Subhydric (8)	Water removed slowly enough to keep the water table at or near surface for most of the year; organic and gleyed mineral soils; permanent seepage < 30 cm below soil surface.	E – G	> 40	0-30	Seepage or permanent water table <30 cm	Variable depending on seepage	Very poor	i, j, k	Wet	0W
Hydric (9)	Water removed so slowly that the water table is at or above the soil surface all year; organic and gleyed mineral soils.	E – G	> 40	0	Permanent surface water table	Variable depending on seepage	Very poor	l	Wet	0W

Tables 2 and 3 show the soil features used to generate the equivalent moisture regime classes and associated AWHC values, as used in TACA GEM, for representative reclaimed sites and natural sites, respectively. The three natural sites vary considerably in AWHC, from a low of 102 mm (High Level) to 196 mm (Fort Chipewyan)(Table 3). A comparison of Table 3 with Table 2 suggests that in terms of AWHC, Fort Chipewyan has subhygric moisture regime, Calling Lake is mesic, while High Level is subxeric.

Table 2. Soil features used to generate the moisture regime classes and associated AWHC values, as used in TACA GEM, for reclaimed sites.

	Soil Moisture Regime				
Soil Features	**Xeric**	**Subxeric**	**Submesic**	**Mesic**	**Subhygric**
Soil Texture[1]	S	LS	SL	SL	L
Soil Rooting Zone Depth (m)	0.6	0.65	0.65	0.89	0.75
Coarse Fragment (%)	24	20	31	38	30
AWSC (mm/m of soil)	154.6	192.3	290.0	290.0	362.5
AWHC (mm)	70	100	130	160	190
Field Capacity (mm/m)	217.6	247.0	373.0	373.0	453.0
Available Field Capacity (mm)	99.2	128.4	167.3	205.8	237.8
Percolation (mm/day)	15.0	10.0	5.0	0.0	-5.0

[1] S=Sandy, LS=Loamy sand, SL=Sandy loam, L=Loam

Table 3. Soil features used to generate the moisture regime classes and associated AWHC values, as used in TACA GEM, for natural sites.

Site	**Fort Chipewyan (subhygric)**	**Calling Lake (mesic)**	**High Level (subxeric)**
Slope position	Mid slope	Mid slope	Mid slope
Soil Texture[1]	L	L	SL
Soil Rooting Zone Depth (m)	0.9	0.60	0.50
Coarse Fragment (%)	40	25	30
AWSC mm/m of soil	362.5	362.5	290.0
AWHC (mm)	196	163	102
Field Capacity mm/m	453.0	453.0	373.0
Available Field Capacity	244.6	203.9	130.6
Percolation (mm/day)	15.0	16.0	13.0

[1] L=Loam, SL=Sandy loam

2.4 Results and Discussion

2.4.1 *Reclaimed and Natural Soils*

Jack pine regeneration was predicted to increase generally through this century on the reclaimed sites and natural site types (Figure 2). By the 2080s, regeneration was predicted to decline slightly on both site types. A comparison between the natural sites and their corresponding moisture regimes on the reclaimed sites showed little quantitative difference in predicted regeneration for High Level (a subxeric site)(Figure 2). Regeneration probabilities for Calling Lake and Fort Chipewyan, however, were lower than the corresponding moisture regimes on reclaimed sites (mesic and subhygric, respectively). This trend by moisture regime was also common to the other two tree species (i.e., white spruce and aspen; data not shown) even though their projected regeneration probabilities on reclaimed sites were quite different (see below).

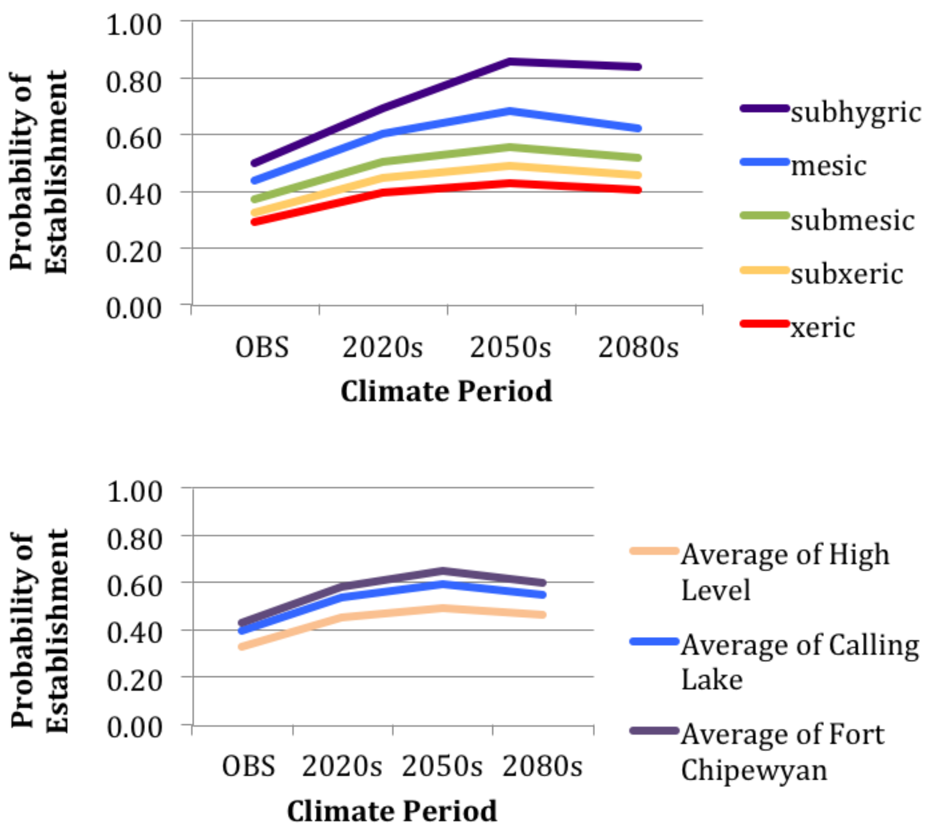

Figure 2. Average probability of jack pine establishment, calculated over simulations conducted using the 6 GCM scenarios (see text), as predicted from TACA GEM. Averages are shown for the current climate (OBS), and climate conditions projected for the 2020s, 2050s, and 2080s, on 5 moisture regimes (xeric, subxeric, submesic, mesic, and subhygric) derived from reclaimed sites (top panel) and 3 natural sites (bottom panel).

The differences between the Calling Lake and Fort Chipewyan sites, and their analogous moisture regimes on reclaimed sites was largely due to the fact that percolation rates were assumed to be higher on those natural sites (cf. Tables 2 and 3). This is because on reclaimed sites, slope position is a key driver of moisture regime, an assumption consistent with the Land Capability Classification System (Alberta Environment 2006). In that respect, mesic and subhygric regimes were assumed to occupy lower slope positions where percolation rates were either neutral (the mesic site) or negative, indicating that water was actually moving into the rooting zone, as might occur in toe slope positions. Note that in the latter case, potential issues associated with salt intrusion are not considered. The three natural sites were all located mid-slope (Table 3). Percolation rates were therefore similar and differences in the moisture regime were thus a function largely of soil properties alone (Table 3). Taken together, these results highlight the limitations of assessing soil moisture regime from only a single component of AWHC (for example, soil properties or slope position).

2.4.2 *Soil Moisture Regime*

Soil moisture regime generated pronounced differences in regeneration probabilities both within a given future time period, and across periods (see Figure 2 upper panel for jack pine, and Figure 3 for aspen and white spruce). As might be expected, regeneration was highest in the wettest moisture regime but declined as the moisture regimes were progressively drier. However, the difference between moisture regimes within a given period also increased over time for all species. This is most likely a consequence of the prediction that growing season moisture deficits will generally increase through the century (Welham and Seely 2011, Figure 14B), a trend that would be exacerbated in the drier moisture regimes. Regular rainfall and relatively short periods of water-deficit are key characteristics of productive landscapes, whereas high rainfall variability and (or) prolonged seasonal drought are generally unsuitable (Audet et al. 2012; see Figure 10). From the perspective of reclamation outcomes, these results suggest soil prescriptions should be developed and/or applied which generate moisture regimes that are submesic and wetter. Drier regimes (subxeric and xeric) appear to introduce a substantially greater average risk that revegetation success in a future climate may be compromised through regeneration failure.

Across climate periods, regeneration in this northern region was generally improved in jack pine (Figure 2 upper panel) and aspen (Figure 3, middle and lower panels) because of warming temperatures and in some scenarios, increases in annual precipitation, predicted under climate change (see Welham and Seely 2011, Figures 13 and 14). This was particularly the case in the wetter moisture regimes (submesic to subhygric) than the subxeric and xeric regimes, probably due to the impact of growing season moisture deficits. Aspen suckering had substantially greater predicted regeneration success than aspen regenerated from seed (cf. Figure 3, middle and lower panels). Suckering is a method of vegetative (asexual) reproduction and each ramet is thus supported in terms of nutrients and water by the parent tree, at least initially. Although seed production can be prolific (Maini 1968), aspen seeds lack endosperm. Seedlings therefore require an immediate source of soil moisture to survive and thus are highly sensitive to drought (Peterson and Peterson 1992). Hence, growth and survival rates should be higher and more

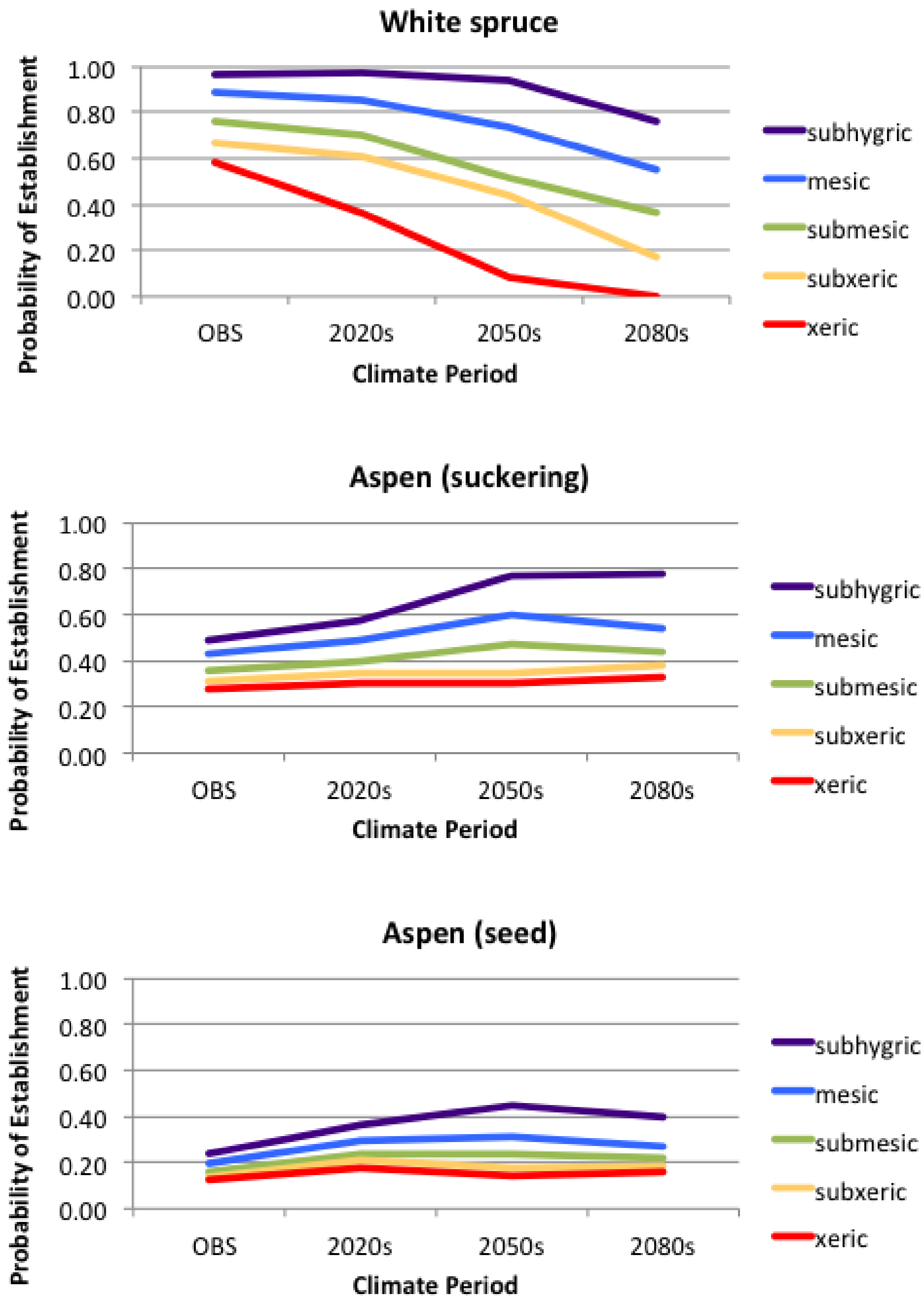

Figure 3. Average probability of establishment in white spruce (upper panel), and aspen – from suckering (middle panel) or seed (lower panel), calculated from simulations conducted using 6 GCM scenarios (see text), as predicted from TACA GEM. Averages are shown for the current climate (OBS), and climate conditions projected for the 2020s, 2050s, and 2080s, on 5 moisture regimes (xeric, subxeric, submesic, mesic, and subhygric) associated with reclaimed sites.

consistent in suckers than seed regeneration because to some extent a developing ramet is insulated from the vagaries of climatic variation.

Predicted trends in white spruce regeneration were in sharp contrast to the other species (Figure 3 upper panel). Spruce regeneration was reduced substantially in future periods to the point where it was predicted to be less than 20% in subxeric and xeric moisture regimes. Surveys by Hogg and Schwarz (1997) showed that planted white spruce produce almost no natural regeneration on dry sites in the southern parkland and grassland zones. Conifer seedling establishment may require a sustained period when soils are moist, a rarity on dry soil moisture regimes and which will become increasingly unlikely as the climate continues to warm later in this century. Very dry site conditions can occur in more northerly regions even today. Hogg and Wein (2005), for example, have reported very poor white spruce regeneration following fire in valley bottoms of the southwestern Yukon despite the fact spruce can produce abundant natural regeneration on cleared farmlands in the boreal forest (Hogg and Schwarz 1997). Although spruce regeneration is generally expected to decline with climate change over this century, on wetter sites the probabilities are still similar to both jack pine and aspen regeneration from suckering (though the trends among species are different; *cf*. Figure 2 upper panel, and Figure 3, upper and middle panels). Spruce is thus a suitable species for wetter sites only, whereas aspen and pine offer greater flexibility in terms of the range in moisture regimes in which they can regenerate.

Species regeneration success is a function of multiple factors some of which work in concert (see Nitschke and Innes 2008b). It is thus difficult to definitively ascribe causality as to why regeneration may be so poor in some cases but not others. Compared to the other species, however, white spruce has the lowest tolerance to drought and heat stress, two key features of climate change. These results indicate that, from a reclamation perspective, the impact of climate change on regeneration requires careful consideration of the tree species and its associated moisture regime. One important caveat to these results, however, is the implicit assumption in TACA that seed is not limiting such that sufficient germinants will be potentially available to support a viable population. As the climate regime becomes progressively warmer, fire frequency and severity is also predicted to increase (Volney and Hirsch 2005). Not only could this affect seedling mortality directly (which is not accounted for in TACA, or in the scenarios/analyses in this report) but trees might also be killed before they attain a size sufficient for seed production.

2.4.3 *Current Reclamation Practices*

Given the sensitivity of tree species establishment to climate and soil properties, as reflected in the moisture regime (MR), a key question is how well might current reclamation prescriptions be expected to perform under climate change? Figure 4 shows the establishment probabilities from TACA for jack pine (left panel) and white spruce (right panel) at four time periods and five MRs. The boundaries for a given MR, as determined by available water holding capacity (AWHC), were derived from Table 1. Above each panel is a series of AWHC values for reclamation prescriptions, and whose range collectively is designed to bracket current practices.

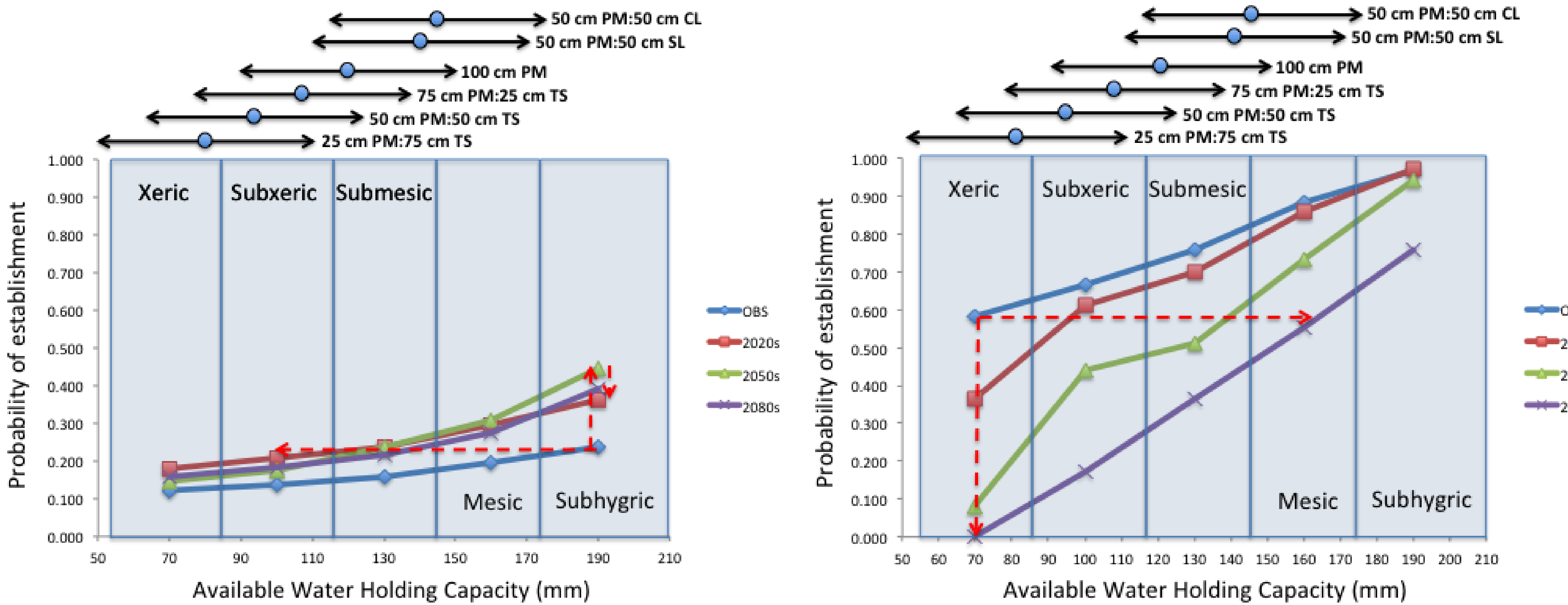

Figure 4. Average probability of establishment in jack pine (left panel), and white spruce (right panel), as predicted from TACA GEM. Averages for the current climate (OBS), and climate conditions projected for the 2020s, 2050s, and 2080s, on 5 moisture regimes (MR; xeric, subxeric, submesic, mesic, and subhygric) as dictated by available water holding capacity (AWHC).

Averages are calculated from simulations conducted using 6 GCM scenarios (see text). Arrows above each panel are the mean AWHC values + 30 mm (see text for details). Red arrows illustrate the change in establishment probabilities across different time periods (vertical) and the change in MR at a given establishment probability (horizontal). Above each panel is a series of AWHC values for reclamation prescriptions, and whose range collectively is designed to bracket current practices.

These were calculated according to procedures described in Alberta Environment (2006). Variation within a given prescription is a result of +30 mm additions and subtractions to AWHC in accordance with potential landscape adjustments that reflect aspect and slope position (Alberta Environment 2006, Table 8).

For single-layer tailings sand reclamation prescriptions, only the deepest P:M mix amendment (100 cm) generated an average AWHC (120 mm) higher than a subxeric MR, with a lower range into the subxeric (90 mm) and a higher range into the mesic MR (150 mm; Figure 4). In the shallowest amendment (25 cm P:M mix), the average AWHC (84 mm) corresponded with a xeric MR, with the lower and upper MR ranges as xeric (54 mm) and subxeric (114 mm). The two-layer prescriptions had similar AWHCs that averaged a high submesic (141 mm; with a silty loam sub layer) to low mesic (145 mm; clay loam sub layer) MR (Figure 4). The lower range was at the high end of the subxeric MR (111 mm and 115 mm, for silty loam and clay loam, respectively). The upper range was in the lower end of the subhygric MR (171 mm and 175 mm, for silty loam and clay loam, respectively).

Single-layer tailings sand prescriptions tended to produce AWHCs on the drier side of the edatopic grid, and no current prescription generated AWHCs equivalent to values found in natural subhygric MRs. For jack pine, however, this is appears not to be problematic from a regeneration perspective (Figure 4, left panel)[5]. Within a given moisture regime, average regeneration probabilities increased over successive time periods, presumably because one or more limiting factors were ameliorated with a warming climate. However, the nature of this relationship varied by MR. Climate change altered regeneration success very little on xeric sites but had an increasing impact on progressively wetter MRs. Differences among the future time periods in regeneration probability were relatively minor, although regeneration appeared to decline by the 2080s. It should be expected that at some point, the climate regime could change enough that all extant species will be negatively affected – perhaps this might be the case in the 2080s and beyond.

Regeneration success also increased across MR (from driest to wettest). Combined with the increase in projected regeneration across subsequent time periods, this means that in the future, current levels of regeneration may occur at relatively drier MRs (Figure 4 left panel). In the subhygric MR, for example, pine regeneration under today's climate is about 20%, which is equivalent to what might be expected in future periods in submesic and even subxeric MRs. From a reclamation perspective, this implies that the fact the subhygric (or even a mesic) MR may not be created with current prescriptions will not be problematic because equivalent jack pine (and aspen) regeneration success is achieved at the drier MRs that do correspond to existing best management practices. This is particularly the case for the two-layer soil replacement

[5] Note that the same conclusion applies to aspen (both seed-origin and from suckering) because both species exhibit the same trend in regeneration probability across time periods (*cf.* Figures 2 and 3, top, and middle and lower panels, respectively).

process, though the recommended one-layer depth of the P:M mix (50 cm) may not always supply sufficient moisture (Figure 4, left panel).

Projections of regeneration success in white spruce contrasted sharply with jack pine and aspen. For spruce, the MR was critical to establishment success, declining significantly both as the MR became drier and across future time periods (within a given MR; Figure 4, right panel). The latter trend was most pronounced in the xeric MR and least pronounced in the subhygric MR. Contrary to pine and aspen, therefore, maintaining current establishment probabilities for white spruce in future plantings may require soil amendments with higher AWHCs. In the xeric MR, for example, projected climate conditions in the 2020s necessitates an increase in average AWHC to subxeric, with a further increase to a submesic MR by the 2050s, and then a mesic MR by the 2080s (Figure 4; right panel). In terms of actual prescriptions, current best management practices appear sufficient to maintain spruce regeneration levels, at least until the 2020s. Beyond that period, the depth of the P:M mix in future one-layer amendments will need to be increased if subsequent establishment is to be maintained at satisfactory levels, with an eventual transition required to a two-layer amendment. This has important implications going forward for mass balance calculations associated with soil amendment materials, particularly given that even in established mines, much of the reclamation effort is scheduled to occur several decades (or more) from now. Hence, demand for suitable material will rise if reclamation prescriptions are adjusted in an effort to maintain spruce establishment under a changing climate regime. This issue is compounded by fact that, according to model projections, no current prescription is likely to generate an AWHC sufficient to offset a subsequent decline in spruce regeneration in the subhygric MR (Figure 4, right panel).

Overall, these results suggest that from the perspective of regeneration, no single set of reclamation prescriptions will be adequate to maintain the current suite of tree species common to the region in future time periods. Nevertheless, current one-layer prescriptions seem adequate for maintaining pine and aspen regeneration, at least on average. Practices governing spruce, in contrast, will need to be transitioned over the next several decades towards an emphasis on constructing two-layer prescriptions, in an effort to minimize the risk of inadequate establishment in future periods. This recommendation is predicated on an assumption that historical performance is an appropriate benchmark and which aligns with the concept of Equivalent Land Capability (ELC). ELC is defined in the *Conservation and Reclamation Regulation* (CRR – s. 1(e)) as the ability of the land to support various uses after conservation and reclamation that is similar though not necessarily identical to the ability that existed prior to an activity being conducted on the land. However, an alternative consideration in the design and evaluation of reclamation prescriptions, particularly for spruce, might be the extent to which present and future regeneration outcomes in natural systems will also be affected by climate change. As our analysis indicated above (see Figure 2), within a given moisture regime regeneration outcomes are similar regardless of site (natural versus reclaimed). Perhaps then the important analysis is the relative extent to which reclaimed prescriptions generate outcomes that differ from natural sites, and how the former should be modified accordingly. In this case, ELC is defined not from a historical perspective but from future anticipated capability.

2.4.4 *Accounting for Variation in Predicted Outcomes*

Differences between GCM models are one of the larger sources of variation (and hence, uncertainty) in projections of climate change. One approach to addressing this uncertainty is to use a series of GCM-emission scenario combinations to bracket potential outcomes (see section 2.2. These are then used as inputs to TACA, and from which average outcomes are derived (as per Figures 2 to 4). Averages, however, are summarized indices that reflect general trends. As such, any variability associated with climate inputs is removed. From a risk management perspective, it is much more useful to have knowledge of the potential range in possible outcomes. This is because each outcome is viewed differently in terms of its costs and benefits. If a particular outcome has especially adverse consequences, reclamation practices might be adjusted to mitigate the risk of its occurrence. Conversely, if all predictions are similar (i.e., with little variation) this suggests that outcomes are relatively robust to climate uncertainty regardless of whether they are viewed as favorable or not.

One metric suitable for estimating variability is the coefficient of variation (CV). Calculated as the ratio of the standard deviation to the mean (s/xbar), the advantage of the CV is that it is unitless and allows for comparison of the relative amounts of variation among populations that have different means (Sokal and Rohlf 1981). This allows CVs to be compared to each other in ways that other measures, like standard deviations or root mean squared residuals, cannot.

Figure 5 shows the CV for the probabilities of establishment from seed in jack pine and aspen, and for aspen suckers. CVs were generally similar though patterns were dependent on the climate period and the MR. In the case of the latter, the CV increased across the climate periods on xeric sites, as well as on subxeric sites for aspen (in both seed and sucker-origin). The correspondence between TACA's projections of average establishment success therefore declined from the 2020s (good to moderate agreement) to the 2080s (generally poor agreement). Given that these sites are of marginal suitability under current conditions, regeneration success is likely to be very sensitive to the changes in climate projected for future periods; hence, the increasing uncertainty around the predicted mean response to climate change on dry sites (see Figures 2 and 3).

Coefficients of variation in predicted regeneration success for jack pine and aspen on wetter MRs showed a different pattern than on the drier MRs (Figure 5). TACA output showed good to moderate agreement in the 2020s, though the best and most consistent agreement among output was in the 2050s. Model predictions then diverged for the 2080s. The latter is likely a consequence of trends in climate data that are used as input for TACA. GCM projections are generally consistent through the first decades of this century but begin to deviate starting in the 2050s and continue to do so thereafter (IPCC AR4 Summary for policy makers; available at www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf). The general concordance in TACA predictions and reasonably low CV on wetter MRs suggests then that the conclusions regarding climate change impacts on regeneration success in jack pine and aspen (see Figures 2 and 3, respectfully) are fairly robust at least through the 2050 climate period.

Overall, there was considerable uncertainty associated with TACA predictions for white spruce particularly in the 2080s (Figure 6), and the trend in CV values differed from the other two species (*cf*. Figure 5). On xeric sites, the CV for spruce reached a peak value of 2.45 in the 2050s, the highest for any species. This value is likely more an artifact of a very low mean value for the regeneration probability (see Figure 3 upper panel) than a true reflection of uncertainty in model outcomes. Given how the CV is calculated (see above), a small denominator can generate very large ratios. Ascribing any interpretation to this value is therefore difficult (Sokal and Rohlf 1981). In the 2080s, however the CV drops to 'zero' on xeric sites. In this case, all of the TACA runs indicated that conditions would be too dry for spruce regeneration by the 2080s.

With the exception of xeric sites, the CV in white spruce regeneration increased across the climate periods indicating progressively lower consistency among TACA predictions. Within a given climate period, however, the CV declined as the MR became wetter (Figure 6). Taken together, these trends likely reflect the fact regeneration success on drier sites is more sensitive to climate variability, and that there is an increase in the variation among GCM climate projections across the time periods.

To evaluate the implications of these results in terms of reclamation practices and policy, a summary of general trends in regeneration probabilities and associated confidence levels for the three tree species is shown in Table 4. Rather than focus on specific values, this table groups the outcomes into classes, as represented by degrees of shading. In one case, for example, the highest regeneration probabilities (> 0.50) are given the same (light grey) shading as the lowest CV values (< 0.25; see Table 4). This is the most desirable pairing since the low CV reflects a consistent result across different TACA simulations in conjunction with the most favorable regeneration probabilities. It provides the greatest confidence in how tree species might respond to a future climate and which reclamation practices should be favoured to minimize uncertainty in outcome. Conversely, the darkest shading indicates the lowest regeneration probabilities (< 0.25) and the least consistency among model predictions (CV > 0.5).

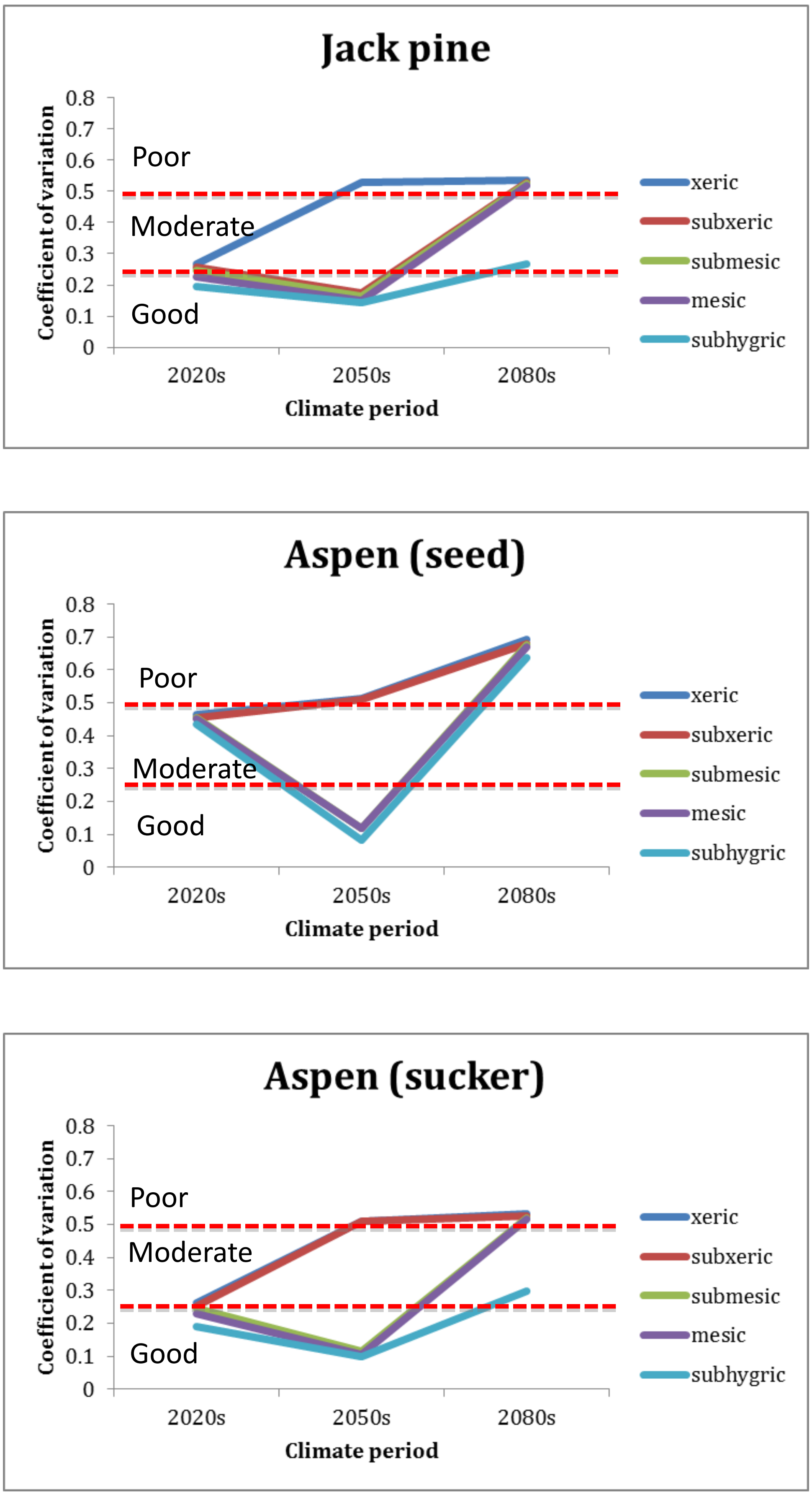

Figure 5. Coefficients of variation (CV) for jack pine (upper panel), and aspen from seed (middle panel) or suckering (lower panel).
CV values are calculated using predictions of regeneration probabilities derived from the TACA model, for the 2020s, 2050s, and 2080s, on 5 moisture regimes (MR; xeric, subxeric, submesic, mesic, and subhygric), for 6 GCM scenarios (see text). Dashed red lines delineate the boundary between good and moderate (CV= 0.25), or moderate to poor (CV=0.50) agreement between model predictions.

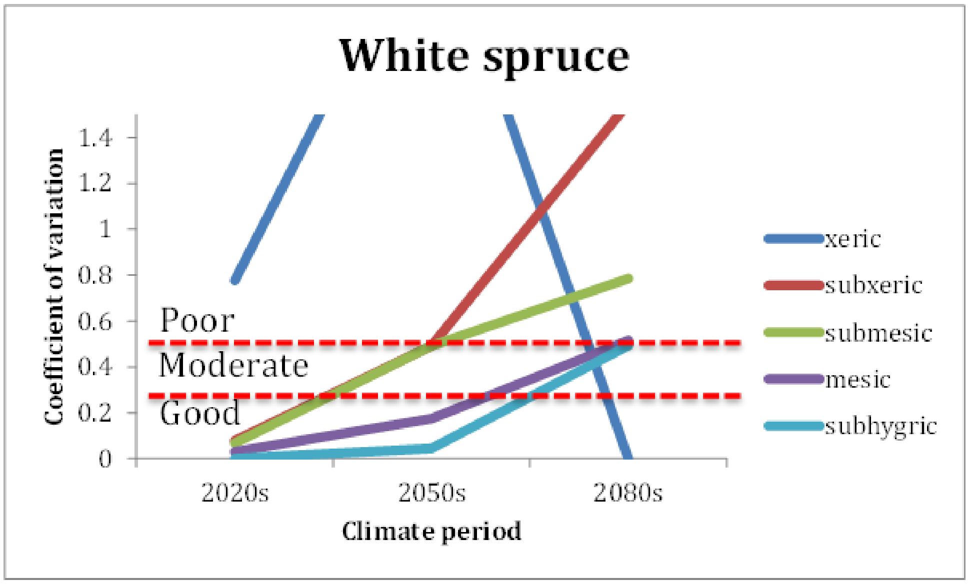

Figure 6. Coefficients of variation (CV) for white spruce.
CV values are calculated using predictions of regeneration probabilities derived from the TACA model, for the 2020s, 2050s, and 2080s, on 5 moisture regimes (MR; xeric, subxeric, submesic, mesic, and subhygric), for 6 GCM scenarios (see text). To maintain clarity within the panel, the CV for the 2050s on xeric sites (2.45) are omitted. Dashed red lines delineate the boundary between good and moderate (CV=0.25), or moderate to poor (CV=0.50) agreement between model predictions.

Reclamation practices that generate the two wettest MRs are most likely to result in successful outcomes (a high CV; they have low risk of an undesirable outcome), at least through the 2050s (Table 4). Drier moisture regimes can have lower regeneration probabilities but results were often highly inconsistent (a high CV) across the climate scenarios. Constructing covers that generate drier moisture regimes thus entails considerably more risk of inadequate regeneration. Similarly, although regeneration was high in the 2080s, for many of the MRs uncertainty in model predictions was also high. However, because of the extended time frame, modifying current reclamation practices or planting prescriptions to mitigate this risk is not warranted. Taken together, these results emphasize the point that the climate will continue to change and highlight the necessity for ongoing investment in this type of analysis to facilitate the process of continuous learning that can form the basis for adaptive management.

Table 4. Predicted regeneration probabilities (Pr(Regen)) and the associated coefficient of variation (CV).
Light grey shading refers to either Pr(Regen) values > 0.50 or CV values < 0.25.
Dark grey shading refers to either Pr(Regen) values < 0.25[cp1] or CV values > 0.50.
Medium grey refers to either Pr(Regen) or CV values ≥ 0.25 and ≤ 0.50 (further details in text).

Jack pine

	2020s		2050s		2080s	
	Pr (Regen)	CV	Pr (Regen)	CV	Pr (Regen)	CV
Xeric	0.40	0.27	0.37	0.53	0.39	0.54
Subxeric	0.45	0.26	0.49	0.17	0.44	0.53
Submesic	0.50	0.25	0.56	0.17	0.50	0.52
Mesic	0.61	0.23	0.69	0.15	0.60	0.52
Subhygric	0.69	0.19	0.86	0.14	0.84	0.27

Aspen (sucker)

	2020s		2050s		2080s	
	Pr (Regen)	CV	Pr (Regen)	CV	Pr (Regen)	CV
Xeric	0.30	0.26	0.30	0.51	0.33	0.53
Subxeric	0.35	0.25	0.35	0.51	0.38	0.53
Submesic	0.40	0.25	0.48	0.12	0.44	0.52
Mesic	0.49	0.23	0.60	0.11	0.54	0.52
Subhygric	0.57	0.19	0.77	0.10	0.78	0.30

Aspen (seed)

	2020s		2050s		2080s	
	Pr (Regen)	CV	Pr (Regen)	CV	Pr (Regen)	CV
Xeric	0.18	0.47	0.15	0.51	0.16	0.69
Subxeric	0.21	0.46	0.17	0.51	0.18	0.68
Submesic	0.24	0.45	0.24	0.12	0.22	0.67
Mesic	0.30	0.45	0.31	0.12	0.27	0.67
Subhygric	0.36	0.43	0.44	0.08	0.39	0.64

White spruce

	2020s		2050s		2080s	
	Pr (Regen)	CV	Pr (Regen)	CV	Pr (Regen)	CV
Xeric	0.36	0.78	0.08	2.45	0.00	0.00
Subxeric	0.61	0.08	0.44	0.49	0.17	1.55
Submesic	0.70	0.07	0.51	0.49	0.37	0.79
Mesic	0.86	0.03	0.73	0.18	0.55	0.52
Subhygric	0.97	0.00	0.94	0.05	0.76	0.49

A final consideration concerns the regeneration of aspen from seed relative to vegetative reproduction by suckering, the latter of which is much more common (Peterson and Peterson 1992). On newly reclaimed sites, aspen are planted as cuttings. Survival and growth of cuttings may be better than from seed (Peterson and Peterson 1992) but is unlikely to be equivalent to suckering because cuttings have no supporting parental connections. Ensuring clonal material is appropriate to site conditions is thus a prerequisite to successful establishment. Recent evidence from a common garden experiment with 242 aspen clones indicated that significant productivity gains might be possible through clonal selection (Gylander et al. 2012). The authors also suggest that planting southern clones in the northern breeding region may counter the negative impacts of warming trends in the latter region.

3 ANALYSIS OF RISKS TO ECOSYSTEM PRODUCTIVITY FROM CLIMATE CHANGE USING FORECAST CLIMATE

The focus of this section (in conjunction with previous work; see Welham and Seely 2011) is to evaluate future ecosystem development within the context of oil sands reclamation using the FORECAST Climate model while incorporating climate change. Historically, primary productivity in high latitudes is temperature limited as a result of a short growing season, a relatively brief frost-free period, and cold soils. Hogg et al. (2005) examined factors affecting growth of western Canadian aspen forests during a fifty-year period. Most of the variation in growth was explained by inter-annual variation in a climate-driven moisture index. Many studies have found a positive response between summer temperatures and/or annual temperatures and the radial growth of white spruce in northern Canada and Alaska (see Schwingruber et al. 1993, Szeicz and MacDonald 1995, and references therein). In addition, white and black spruce recruitment has been positively correlated with increases in summer temperatures (MacDonald et al. 1998). A warmer and/or wetter climate could thus ameliorate one or more limiting factors (see, for example, MacDonald et al. 1998) with the result that growth rates rise through this century (Welham and Seely 2011; see also Kellomaki et al. 2008). Longer, warmer summers, however, could result in lower tree growth if accompanied by prolonged periods of water stress (Fritts 1976, Kozlowski and Pallardy 1997).

Despite an increase in tree growth, future ecosystem productivity could still decline overall if mortality rates are higher. Drought-related mortality has also been documented in aspen (Hogg et al. 2008) and white spruce (Wilmking et al. 2004), two species common in the oil sands region. In our Phase II analysis, stand-level mortality was built into the FORECAST Climate model as a function of moisture stress (calculated as a transpiration deficit index; TDI). TDI is calculated as the relative difference between plant demand for water and what it is actually able to take up from the soil (Welham and Seely 2011 provide a more detailed description). An estimated TDI value of 0.35 (35% below annual demand) was used as the mortality threshold (see s. 3.1.1 for further discussion). When the TDI value for a given species exceeded the threshold in a given year, a species-specific mortality rate was imposed on the population. Though suitable as a first approximation, this approach is overly simplistic. First, the physiological mechanisms underlying drought survival and mortality are complex and poorly understood (see McDowell et al. 2008). Second, while average climatic conditions are changing, climatic variability is also increasing (see Welham and Seely 2011) and which has been correlated with tree mortality events (Daniels et al. 2011). In this Phase III analysis, three mechanisms were evaluated by which moisture deficit can increase mortality risk: (a) as a binary variable, (b) as a continuous variable, and (c) cumulatively across successive years[6].

The binary approach utilizes the same procedure as in Phase II (see Welham and Seely 2011, for details). In this case, however, a range of thresholds was employed in conjunction with different mortality rates. This method was deemed unsatisfactory because it generated unrealistic mortality events. It was therefore not given further consideration. Both the second and third approaches were utilized in deriving mortality estimates (details below).

3.1 Materials and Methods

3.1.1 *FORECAST Climate*

FORECAST Climate is an extension of the FORECAST model (Kimmins et al. 1999), a management-oriented, stand-level forest growth simulator. FORECAST has been under development and application for more than four decades and its output has been evaluated against field data for growth, yield, ecophysiological and soil variables (Bi et al. 2007, Blanco et al. 2007, Seely et al. 2008).

FORECAST employs a hybrid approach whereby local growth and yield data are used to derive estimates of the rates of key ecosystem processes related to the productivity and resource requirements of selected species. This information is combined with data describing rates of decomposition, nutrient cycling, light competition, and other ecosystem properties to simulate

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[6] It should be noted that the actual mechanisms by which moisture stress can act to influence mortality are varied and complex (as reviewed in McDowell et al. 2008). Our analysis considers only the ultimate impact of stress (namely, mortality) without any account for precisely how mortality occurs.

forest growth under changing management conditions (Figure 7). Modifications to the various processes represented within FORECAST to account for the influence of climate are described elsewhere (Kimmins et al. 2010, Welham and Seely 2011). Changes specific to the work conducted in Phase III are described below.

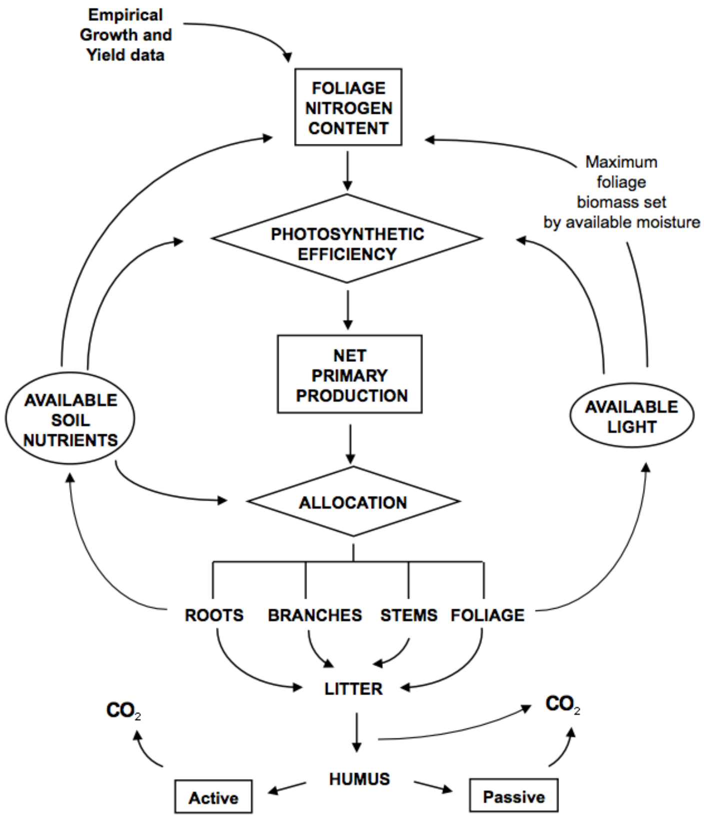

Figure 7. A schematic illustration of the key ecosystem processes and flows represented in FORECAST.

3.1.1.1 ForWaDy: The Forest Hydrology Submodel used in FORECAST Climate

ForWaDy (Forest Water Dynamics; Seely et al. 1997) is a vegetation-oriented, forest hydrology model. It has been evaluated against time-sequence field measured moisture content data from oil sands reclamation covers (Seely at al. 2006). The model can be used as a stand-alone application but is integrated within FORECAST Climate where it is coupled to the main tree growth engine (Kimmins et al. 2010, Seely and Welham 2010, Welham and Seely 2011).

As part of typical quality assurance-quality control tests, an inconsistency in the calculation of the Transpirational Deficit Index (TDI; a measure of available moisture) was discovered and corrected. This lead to a small overestimation of the TDI in the historical climate dataset relative to the climate change simulations. In addition, minor changes were made to aspen, spruce and understory vegetation hydrologic parameters (Table 5) to render them consistent with the corrected TDI calculation and the new mortality function (see below).

The ForWaDy calibration data used within FORECAST Climate are listed in Tables 5 and 6.

3.1.1.2 Representation of Drought Mortality: New Function

In the Phase II runs, drought mortality was simulated using a threshold function. The efficacy of this approach was limited because it did not allow for an increase in mortality rates with increasing levels of water stress, nor did it take into consideration that extended drought periods can lead to elevated levels or mortality (see, for example, Hogg et al. 2008).

A new drought mortality function was developed and implemented within FORECAST Climate to better represent these effects. The new continuous function simulates drought mortality using a two-year running average of a species-specific TDI as a predictor of annual mortality (Figure 8). The 2-year running average allows for a reduced drought mortality when a dry year is preceded or followed by a wet year, but will compound mortality in consecutive dry years. An exponential sigmoidal function curve was selected as a good approximation of the compounded increase in mortality associated with consecutive drought years (see, for example, Hogg et al. 2008). The amplitude of the function curve was fitted to historical climate data for each species so that mortality rates were consistent with empirical observations of mortality events. Two different mortality curves (low and high) were simulated for each tree species to explore the sensitivity of the model to assumptions regarding tree susceptibility to drought stress (Figure 8).

Table 5. Parameter values used to simulate evapotranspiration in ForWaDy.
Italicized values have been updated relative to the Phase II analysis (Welham and Seely 2011).

SPECIES	**Maximum LAI**[1]			**Canopy**		**Permanent Wilting Point** (%)				**Max. Root Depth**
	Submesic	Mesic	Subhygric	Albedo	Resistance[2]	Humus	Submesic	Mesic	Subhygric	(cm)
Aspen	2.0	3.0	3.5	0.12	*0.1*	*0.12*	0.10	*0.16*	*0.27*	100
White spruce	4.0	4.25	4.5	0.12	0.15	*0.11*	0.11	*0.13*	*0.23*	75
Jack pine	2.5	3.0	3.5	0.12	0.30	0.08	0.07	0.12	0.21	110
Grass	-	-	-	0.14	0.25	0.10	*0.06*	0.13	0.23	75
Mid-seral Forb	-	-	-	0.12	*0.10*	0.10	*0.06*	0.13	0.23	75
Hazelnut	-	-	-	0.12	*0.07*	0.15	*0.11*	0.18	0.32	75
Green Alder	-	-	-	0.12	*0.07*	0.13	*0.10*	0.17	0.30	75

[1] Data on leaf area index (LAI) are not required for understory foliage biomass.

[2] Refers to stomatal resistance to water loss from leaves.

Table 6. Parameter values in ForWaDy for simulating soil water availability by ecosite.

Ecosite	**Edaphic conditions**	**Soil texture class**	**Coarse fragment %**	**Mineral soil depth (cm)**	**Initial snow pack (mm)**
a1	subxeric poor	Loamy sand	45	45	60
d1, d2, d3	mesic medium	Silt loam	25	85	125

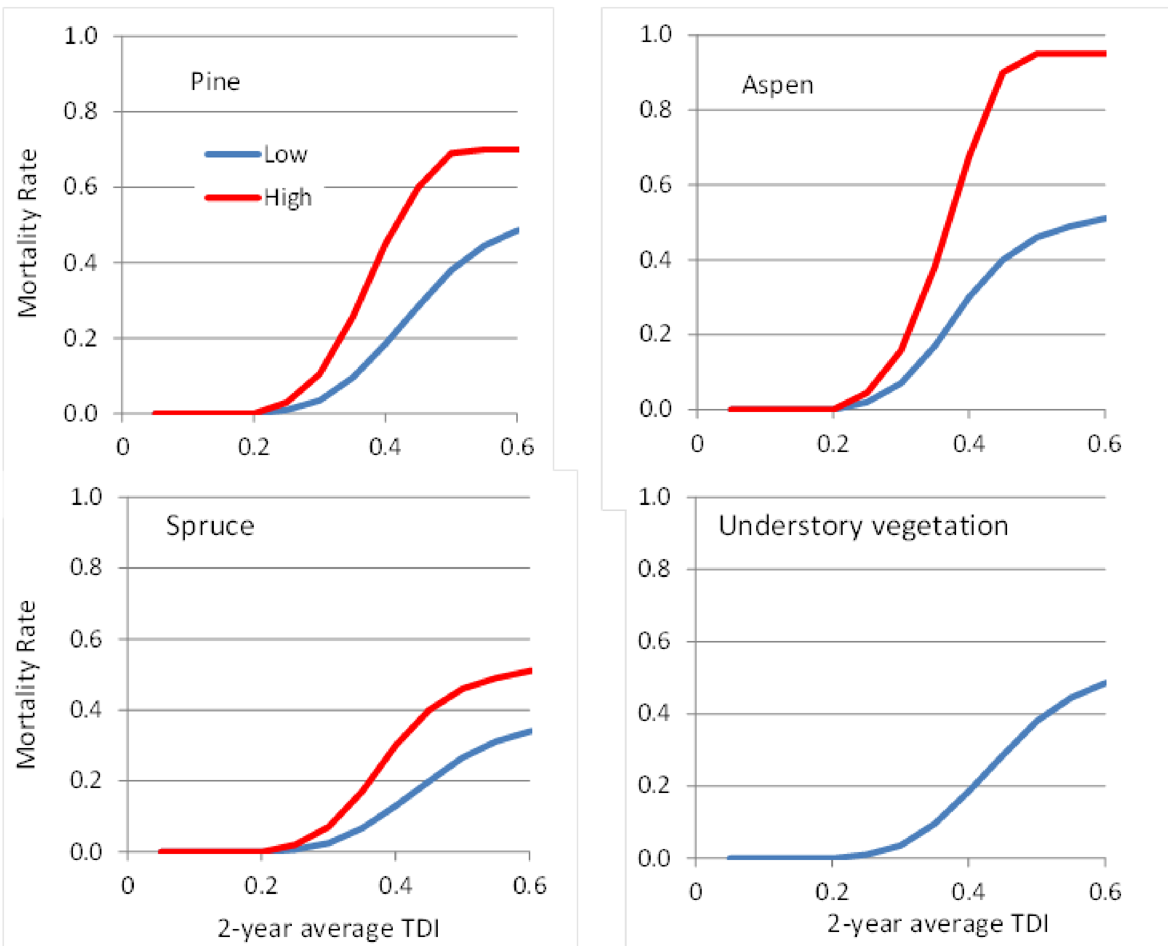

Figure 8. Illustration of the function curves (signifying high and low rates) used to simulate drought-related mortality for each tree species in FORECAST Climate.
Only a single curve was used for understory vegetation.

3.1.2 *Climate Change Scenarios*

To simulate the effects of a changing climate, five climate-change models and associated emissions scenarios were utilized (Table 7). The additional A2 scenario used in the TACA analysis (Section 2.2) was not included as it was very similar to the existing A2 (A) scenario. A complete description of their derivation and application is provided in the Phase II report (Welham and Seely 2011). The model was set up to simulate stand growth and development for a 100-year period beginning in 2010. Historical data from the Fort McMurray climate station were used as a reference and for downscaling.

Table 7. Climate models and scenarios selected to simulate climate change in 2020, 2050 and 2080.

Model	Scenario	General effect[1]
CCSRNIES	A1 F1	Warmer, drier
CGCM2	B23	Cooler, drier
HADCM3	A2 A	Warmer, wetter
HADCM3	B2 B	Median conditions
NCARPCM	A1 B	Cooler, wetter

[1] As compared to median climate change conditions (see Barrow and Yu 2005)

Summarized output from these climate runs is provided in Figure 9.

3.1.3 *Model Application*

Three representative ecosites were simulated (a1, d1, and d3; see Beckingham and Archibald 1996) with 6 climate scenarios, 5 representing climate-change (as per Table 7) and 1 historical scenario, and the two mortality functions for each species (see Figure 8). Regeneration assumptions for each ecosite are provided in Table 8.

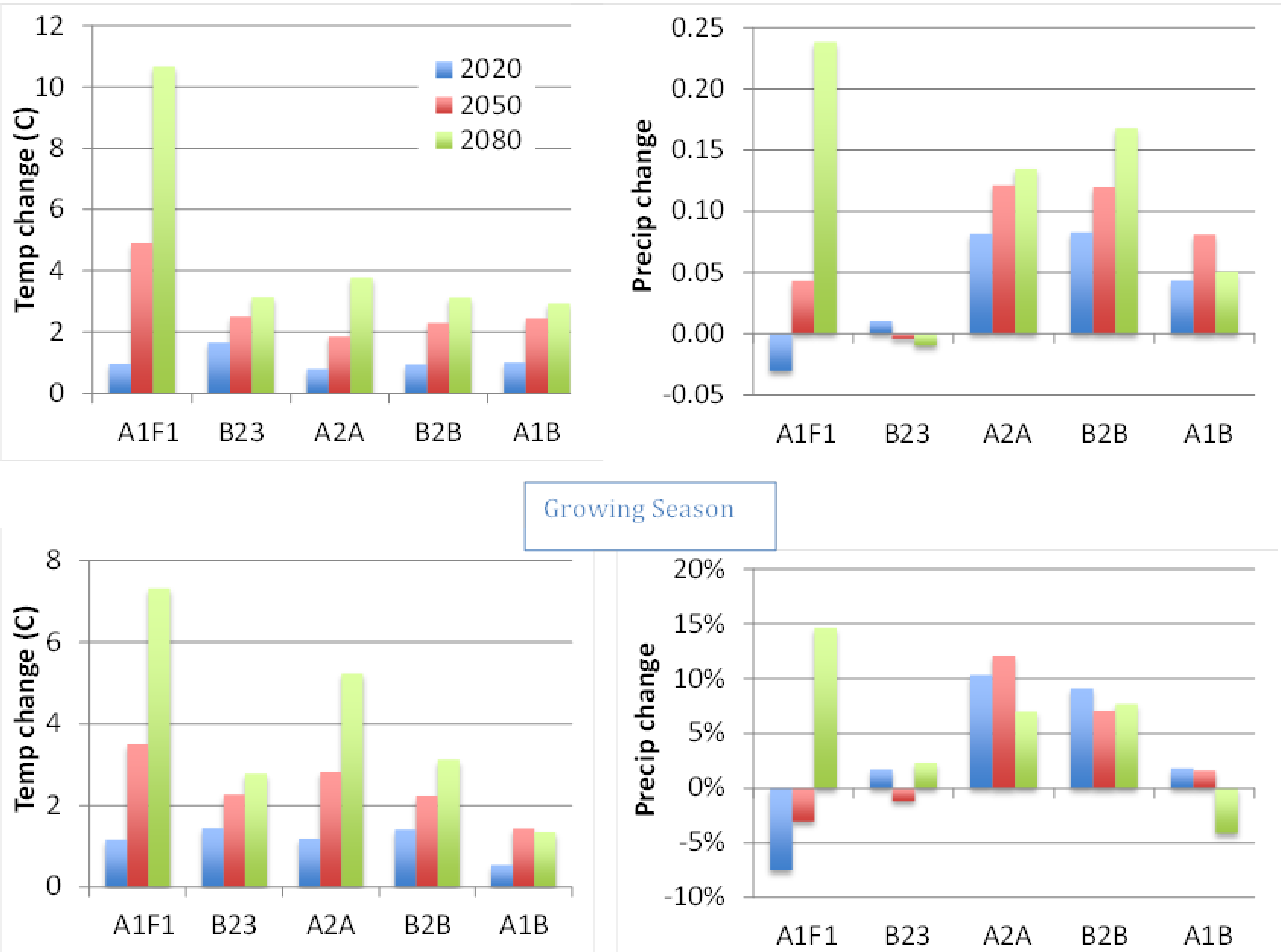

Figure 9. Changes in mean temperature (left) and total precipitation (right) in Fort McMurray, Alberta during three time periods (2020s, 2050s, and 2080s), as projected from five climate-change scenarios.
The top panels show annual changes while the bottom show changes for the growing season (May-Aug). Note that changes are relative to the 1961 to 1990 baseline period.

Table 8. Regeneration assumptions used for each of the different ecosites simulated within FORECAST Climate.

Ecosite	**SI[1]**	**Sp[2]**	**SPH[3]**	**Und. Veg.[4]**
a1	14	Pj	2,500	MSF, GA
d1	18	At	2,500	MSF, GA, HZ
d3	18	Sw	2,500	MSF, GA, HZ

[1] Starting site index. SI is not fixed for a given site within FORECAST Climate and thus can vary throughout the simulation.
[2] Pj – jack pine, At – Trembling aspen, Sw – White spruce
[3] Planting density (stems per ha).
[4] Understory vegetation. MSF – Mid-seral forb, GA – Green alder, HZ – Hazelnut. All runs included a grass.

3.2 Results and Discussion

3.2.1 *Risk of Drought*

Drought is anticipated to be an increasingly important limiting factor to plant productivity and survival in the Fort McMurray region despite the prediction from global circulation climate models that temperature and total and growing season precipitation, will increase through this century (Figure 9). While this might appear paradoxical, moisture limitation can be manifested in two ways. First, the projected increases in temperature (Figure 9) will result in higher transpirational demand (see below). Plants will therefore be drawing greater amounts of moisture from the soil thereby increasing the risk of a shortage. Higher temperatures also increase evaporation losses meaning that less water will enter the soil and thus be available to plants. Second, moisture limitation (or availability) is dependent more on precipitation patterns than total amounts. Deserts are a classic example of this phenomenon where total precipitation can be very low but rainfall is concentrated in a very brief period. Plant growth and reproductive activity is thus timed to coincide with this period though because of limited total moisture, annual primary productivity is low. An example of the distinction between timing and precipitation amounts for the Fort McMurray region is shown in Figure 10. Over the period from 1953 to 2012, total growing season precipitation has remained essentially unchanged at around 300 mm. If, however, the 60-year climate record is divided into four even sub-periods of 15 years, the pattern of drought years (defined as either < 250 mm in a given year, or consecutive years with < 500 mm total) is very different.

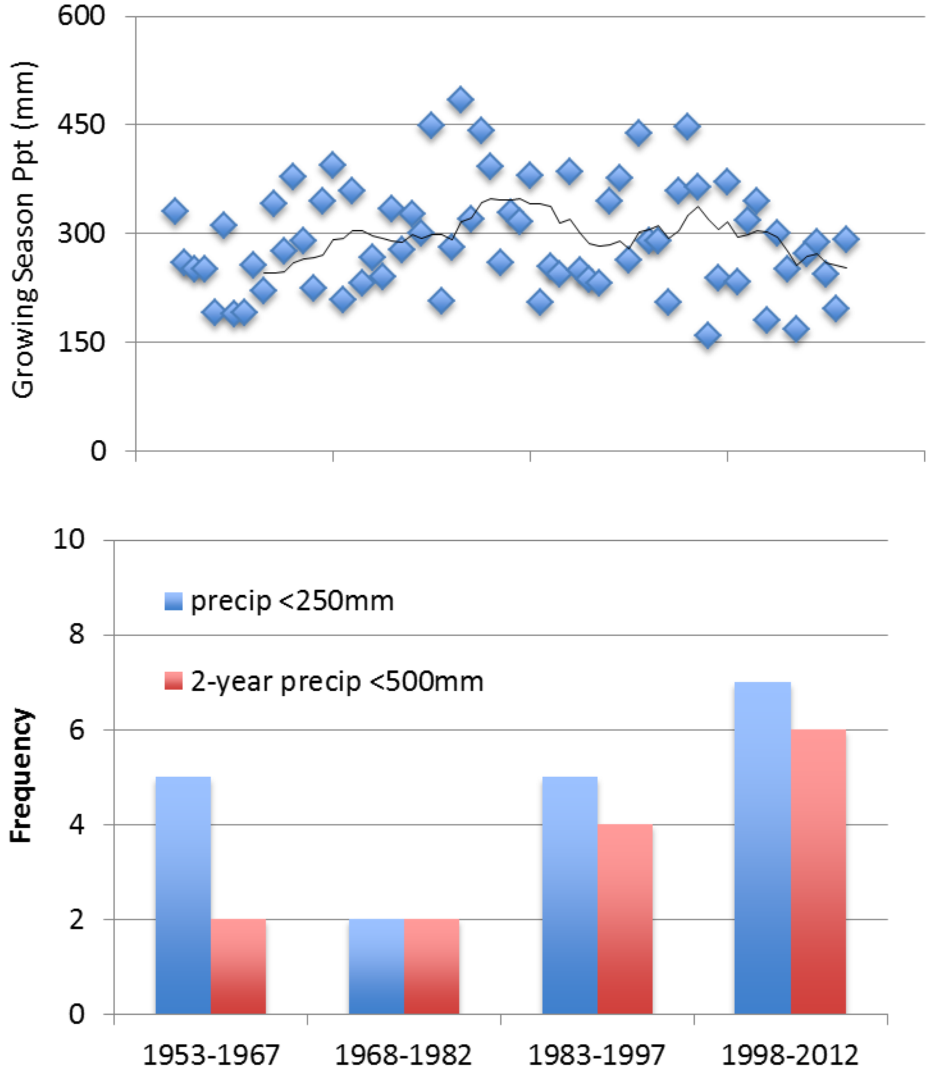

Figure 10. Fort McMurray growing season precipitation.
Top panel: Historical climate data showing total growing season (May to September) precipitation from 1953 to 2012. The trend line represents the 10-yr moving average.
Bottom panel: Frequency of years when total growing season precipitation (GSP) was less than 250 mm in a single year, or the frequency when GSP in two consecutive years was below 500 mm.
Data are from the Fort McMurray weather station.

3.2.2 *Sensitivity to Drought*

3.2.2.1 Mortality

A comparison of drought-related mortality for climate scenarios based on historical trends and future trend projections is shown in Figure 11. Jack pine (ecosite a1) showed very little mortality under the historical climate regime, at either of the mortality rates. Empirical reports of drought-related mortality in jack pine are relatively rare. Yarranton and Yarranton (1975) reconstructed the demography of a jack pine stand in Ontario. Located on an 'overdrained' site, pulses in mortality appeared to be related to periods of severe drought. The authors also pointed out that data from nearby jack pine stands located on wetter sites exhibited very little drought-related mortality. Unfortunately, a quantitative assessment of site conditions (in terms of moisture storage capacity) was not provided (see Yarranton and Yarranton 1975) and so a direct comparison with our results is not possible.

In the case of aspen (ecosite d1) and spruce (ecosite d3), drought-related mortality events under the historical climate regime were not uncommon in the simulations (see Figure 11). Empirical evidence indicates high mortality of aspen following severe drought has occurred along the southern edge of the Canadian boreal forest (Michaelian et al. 2011). A widespread increase in tree mortality (of various species) through the western US and southwestern BC has also been reported, with water deficit a likely contributor (van Mantgem et al. 2009). Climate-induced regeneration failure has been documented in spruce (Hogg and Swartz 1997), as well as reduced growth because of drought stress (Barber et al. 2000, McGuire et al. 2010).

Projections of future climate conditions generated mixed results in terms of mortality, depending on the emission scenario. In general, mortality was equal to or lower than that projected using the historical climate data for aspen (d1) and spruce (d3)(Figure 11). In the case of jack pine, the historical regime generated little mortality and future climate regimes thus tended to increase mortality. Given that primary productivity in high latitudes is temperature limited, a warming climate thus has the potential to improve survival of aspen and spruce, at least for some emission scenarios. This appears not to be the case for jack pine, a species that tends to occupy sites where drought is already problematic (Yarranton and Yarranton 1975). Within a given species, there were peaks in mortality under the A1B and B2B emission scenarios that exceeded historical rates (Figure 11). Peaks in mortality are a consequence of consecutive years when moisture was severely limited and trees were thus moisture stressed (see Figure 13, for examples of this phenomenon). The highest peaks and most consistent increase in mortality, however, occurred under the A1FI emissions scenario for all species. This scenario reflects a future world of very rapid economic growth and intensive use of fossil fuels (Barrow and Yu 2005, Table 1). Hence, its climate-driven projections are for warmer and drier conditions than most of the alternatives (Table 7). Though A1FI was considered a pessimistic outcome (Barrow and Yu 2005), current evidence indicates that, in fact, it may be close to reality (see below).

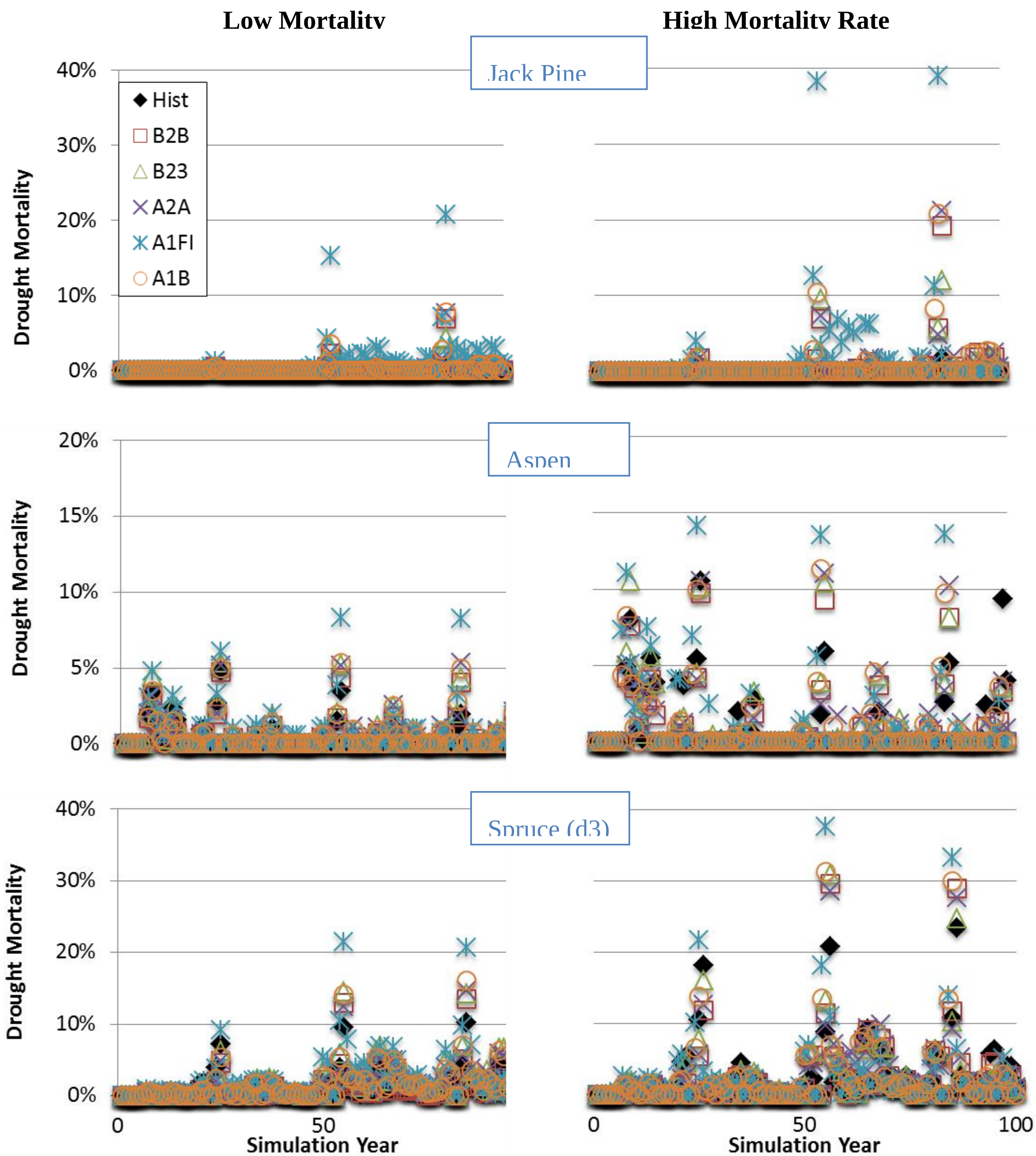

Figure 11. Tree mortality by ecosite for five climate change scenarios, and a historical climate scenario.
Left column is for a low mortality rate and right column for a high mortality rate. Note differences in the abscissa between panels.

For given mortality rate, pine and spruce appear generally robust to drought conditions at least over the next several decades, regardless of the climate regime (Figure 11). Thereafter, mortality then tended to increase (i.e., later in the century; Figure 11). In absolute terms, pine is projected to have the lowest overall drought-related mortality (the exception being the A1FI emission scenario) while spruce is projected to have the highest mortality, particularly late in the century.

Aspen mortality was sensitive even to current climate conditions and showed a slight increase over time. Empirical studies show that severe aspen dieback has already been recorded in the 1990s (Hogg et al. 2002), and that aspen growth is strongly tied to available moisture (Hogg et al. 2005). It was hypothesized that mortality was caused by a combination of climatic factors (drought and early spring thaw-freeze events), multiple-year defoliation by the forest tent caterpillar (*Malacosoma disstria* Hbn.), and damage by fungal pathogens (Hogg et al. 2005, and references therein). None of our mortality estimates were as severe as the reported results. This may be because the climate scenarios we used did not successfully capture the full range of adverse conditions experienced in the study areas. In addition, the documented sites may have possessed unusual limitations associated with soil physical properties that exacerbated the effects of drought conditions (Hogg et al. 2008; see also section 2.4.1). These results highlight the importance of accounting for local climate and soil conditions when making projections of potential impacts and outcomes.

3.2.2.2 Volume Production

Assumptions regarding tree sensitivity to drought stress had a significant impact on volume production and its relation to climate change. When the mortality rate was low (i.e., species were robust to moisture stress), volume production under climate change always exceeded that projected under the historical climate regime (Figure 12). Primary productivity in high latitudes is temperature limited as a result of a short growing season, a relatively brief frost-free period, and cold soils (see, for example, McGuire et al. 2010). In this respect, the positive impacts of a warmer climate outweighed the negative effect of drought stress on survival (Figure 11). If species were less tolerant of moisture stress (i.e., the mortality rate function was high) climate change had a negative impact on stand-level productivity later in the century, though how much depended on the species and a given emissions scenario (see below).

An illustration of how drought stress is affected by climate is provided in Figure 13. In the first two decades of the simulation, there is little difference in drought stress (i.e., the water stress index) between the historical and future climate regimes. Differences become more pronounced thereafter, however, as climate change induces greater differences in the water stress index. Jack pine (the a1 ecosite) shows the highest moisture stress largely because it occupies a coarse textured soil (Table 6) with a low soil storage capacity (Welham and Seely 2011).

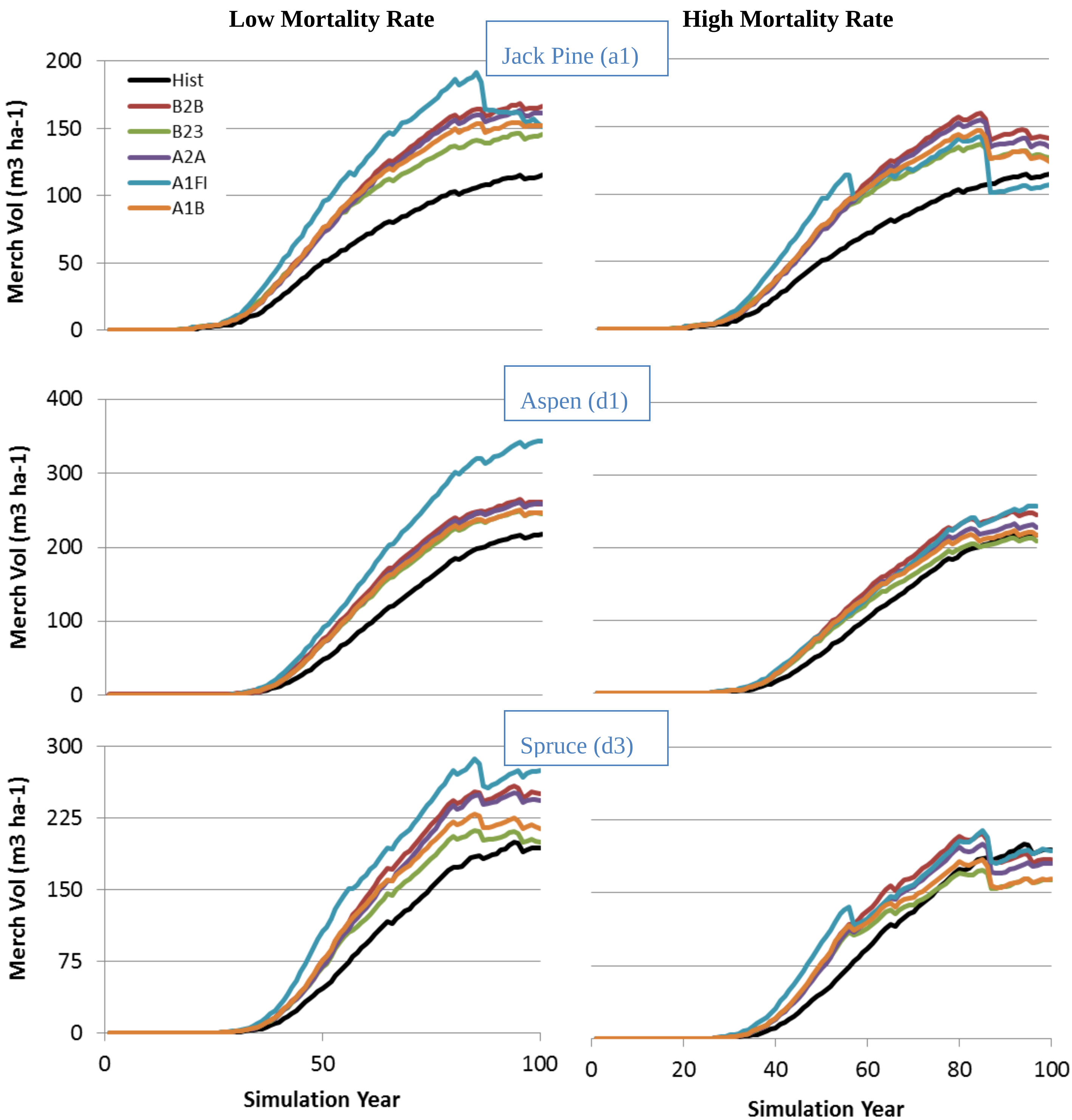

Figure 12. Merchantable volume production by ecosite for five climate change scenarios, and a historical climate scenario.
Left column is low mortality rate; right column is high mortality rate.
Note differences in the abscissa between panels.

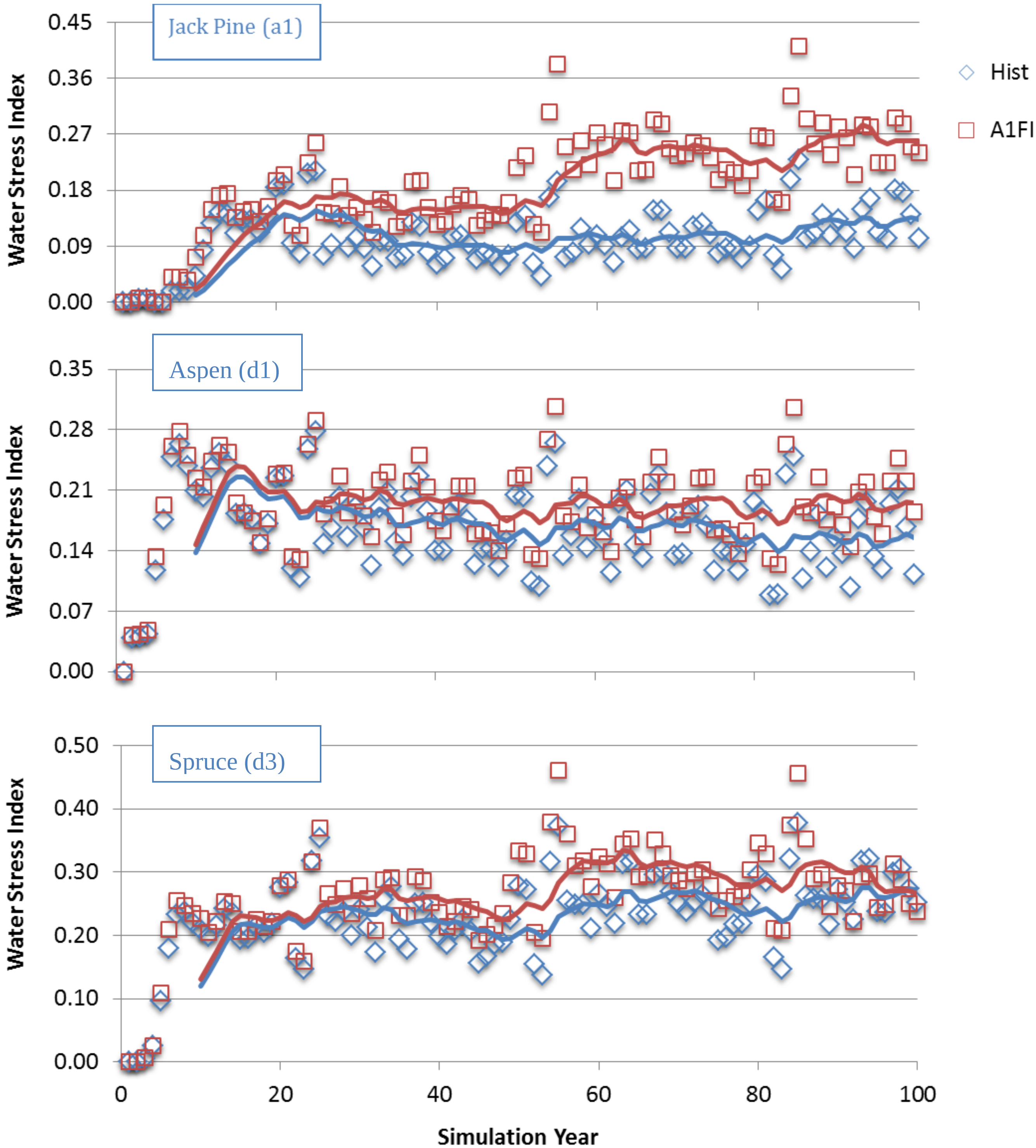

Figure 13. Effect of climate change on the simulated water stress index by ecosite.
Only the historical and A1FI climate scenarios are shown.
Lines represent a 10-year moving average.
Note difference scales on the abscissa among panels.

Climate Response Index (CRI) is a metric calculated in FORECAST Climate that integrates the impact of temperature and precipitation. It thus serves as a proxy measure of climate-related growth conditions (see Welham and Seely 2011, for explanation, where it is referred to as CRIgrowth). Figure 14 illustrates the CRI for the A1FI emissions scenario in comparison with CRI values calculated using the historical climate regime. In any given year, the A1FI scenario generates higher CRI values than occur historically. Note that as might be expected, across the three ecosites the CRI is inversely related to the water stress index (*cf*. Figures 13 and 14). Another useful metric for evaluating how climate impacts productivity is the Decomposition Response Index (DRI). The DRI is calculated within FORECAST Climate as a means for indexing decomposition (i.e., nutrient availability) to temperature and moisture (see Welham and Seely 2011 for explanation, where it is referred to as CRIdecomp). DRI is higher under the A1FI scenario versus historical conditions (Figure 15).

Taken together, both the CRI and DRI illustrate that in this northerly region there are potential benefits to a warmer climate. Whether those benefits are sufficient to outweigh the detrimental impacts of moisture stress, however, is less clear. Volume production is the same or higher under climate change as compared to the historical climate regime over the next 70 years, regardless of a species' sensitivity to moisture stress (i.e., the low versus high mortality rate; Figure 12). If species are relatively drought tolerant (a low mortality rate) then the higher productivity under climate change could be sustained through this century. If, however, species are relatively intolerant to moisture stress (i.e., their mortality rate function was high) climate change will have a negative impact on stand-level productivity later in the century, though how much depends on the species and a given emissions scenario (Figure 12). In the case of spruce (ecosite d3), for example, stand-level volumes would decline to below historical levels. Productivity in aspen would decline to levels generally similar to historical conditions. Jack pine volumes would still be higher than historical for all except the A1FI emissions scenario (Figure 12). In the latter case, mortality is sufficiently high (see Figure 11) that it offsets any benefits a warming climate might provide, particularly during later periods when drought exceeded mortality thresholds and triggered sharp drops in volume.

These conclusions are applicable when impacts are considered at the stand level. It is important to consider the tradeoffs that will occur at a broader spatial scale. If productivity is enhanced, for example, this will result in greater rates of canopy interception and evapotranspiration. Less water will therefore be available to supply surrounding wetlands. Hence, although detailed analyses (as in this report) are necessary to elucidate potential impacts of climate change, their implications should also be evaluated at the appropriate spatial and temporal scales.

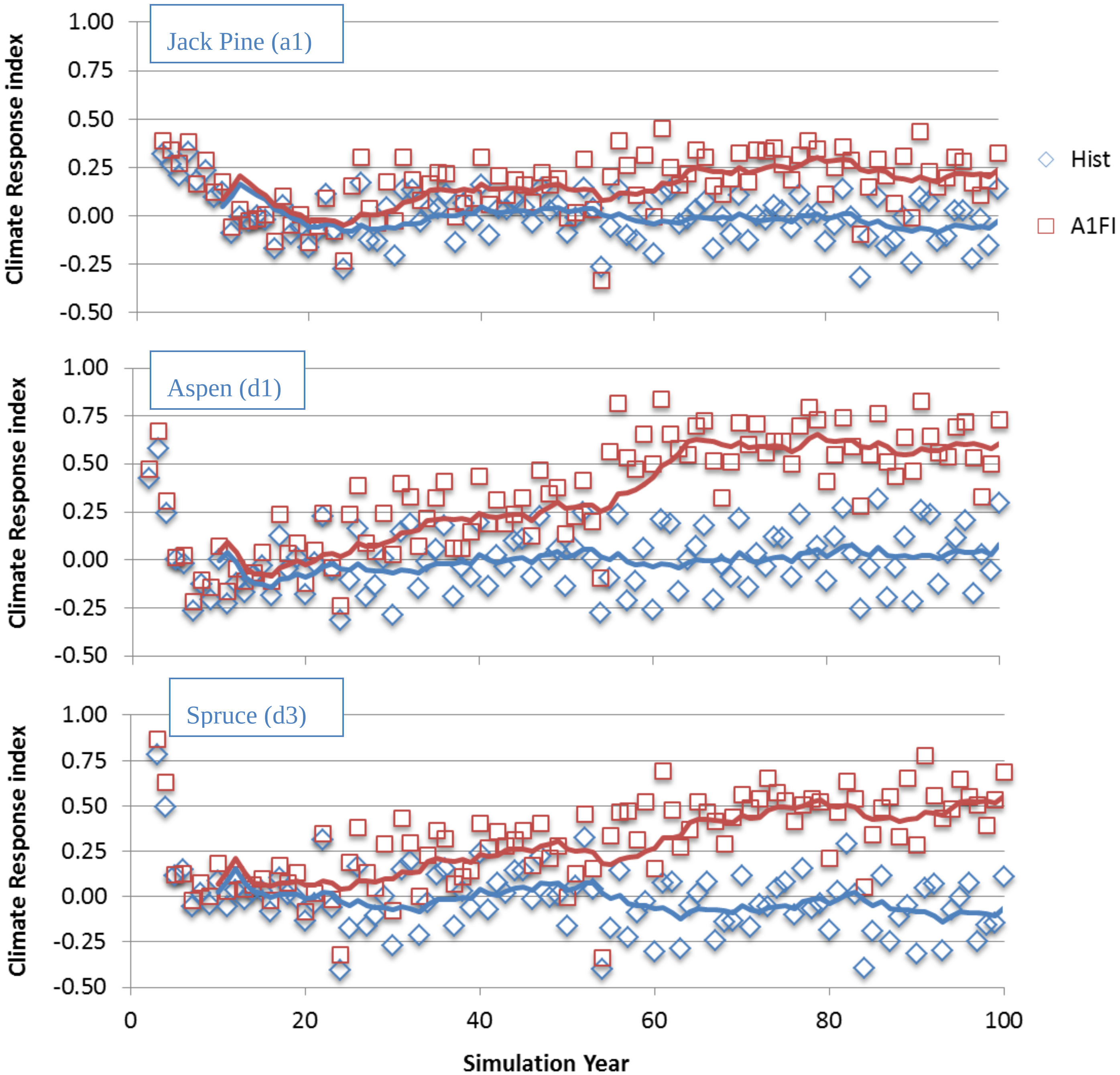

Figure 14. Effect of climate change on the simulated Climate Response Index by ecosite. Only the historical and A1FI climate scenarios are shown. Lines represent 10-year moving averages.

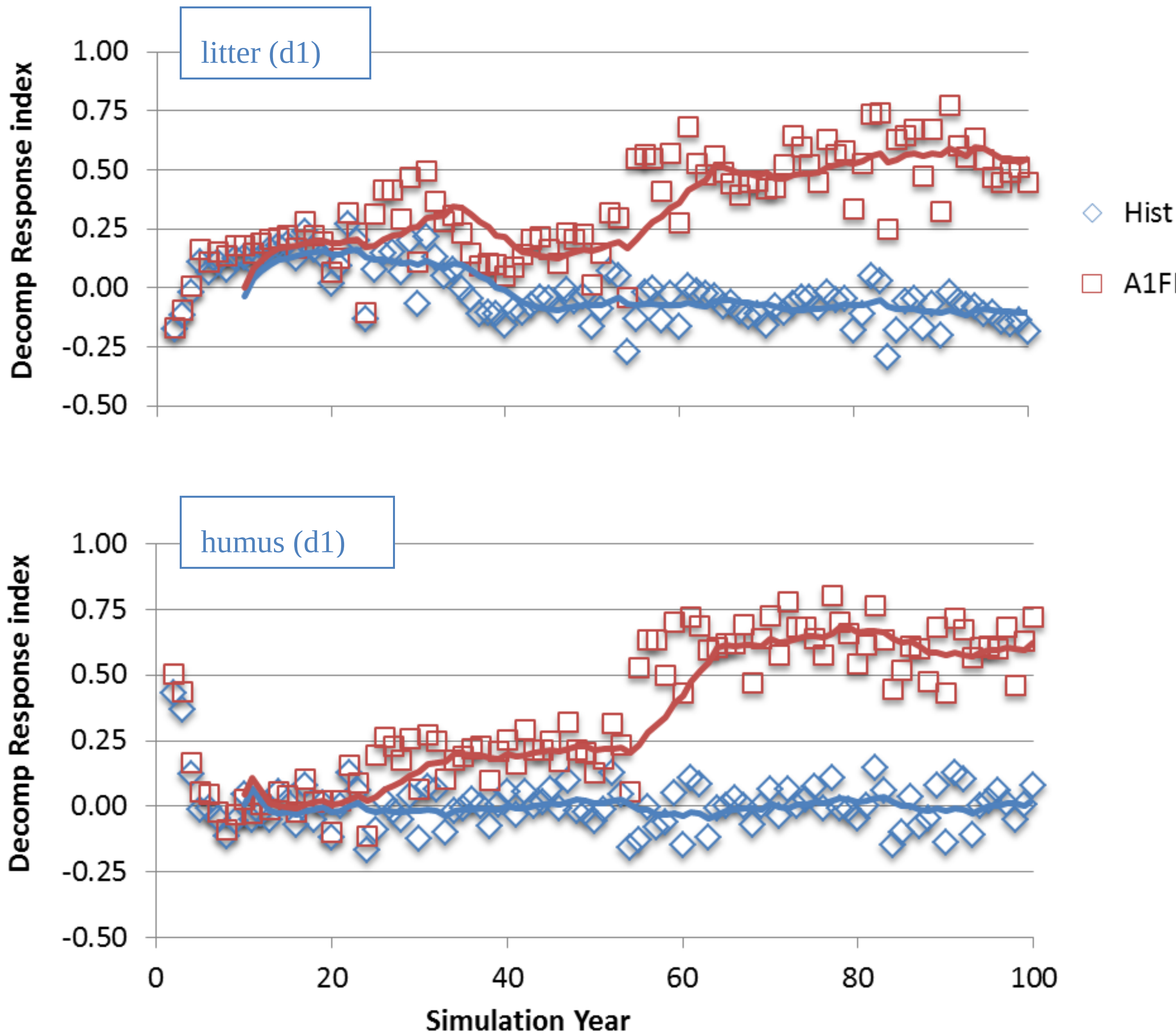

Figure 15. Effect of climate change on the simulated Decomposition Response Index for litter and humus in the d1 ecosite.
Results are for the historical and A1FI climate scenarios. Lines represent a 10-year moving average.

3.2.3 *Implications for Oil Sands Reclamation*

Informed decision-making and policy regarding best management practices and expected outcomes from reclamation are heavily reliant on models and modeling exercises. This is because empirical data to guide management are generally lacking and conditions (climate, for example) are changing such that practices derived from historical experience are of limited utility. Figure 10 is a case in point. It shows that the frequency of years where growing season precipitation was less than 250 mm (a level for which significant water stress would be expected based upon modelling results) has been steadily increasing over the last four decades. Similarly, the frequency of consecutive years with combined growing season precipitation less than 500 mm increased 3-fold over the same period. Unfortunately, there is considerable variability around outcomes when modeling future climatic conditions, in part because projections of CO_2 emissions are highly uncertain. This is evident in the results presented here and in section 2. Recent empirical estimates from the International Energy Agency (IEA) indicate that between 2003 and 2008, global emissions had been rising at a rate faster than the IPCC worst-case scenario (A1FI) (www.iea.org/stats/index.asp). Although emissions dropped in 2009, 2010 saw the largest single year increase in global human CO_2 emissions from energy (fossil fuels). Hence, emissions appear to be tracking much more closely to the A1FI scenario once again (Figure 16). This suggests that the modeled projections here may be more closely aligned with scenarios that project warmer than median conditions (A1FI and A2; see Table 7).

Despite the uncertainty in model projections, several key points emerge from the model simulations. A warming climate acts to mitigate temperature as a limiting factor to stand productivity, in terms of decomposition (Figure 15) and when temperature and precipitation are integrated within proxy measure of climate-related growth conditions (Figure 14). These benefits, however, could be negated by increased mortality from drought stress (Figures 11 and 13). In the case of pine and spruce, however, mortality in established trees should not become problematic (beyond 'normal' background rates) until at least mid-century. Aspen shows no consistent trend in terms of drought sensitivity. Taken together, this suggests that current reclamation practices should be capable of maintaining adequate growth over the mid-term, assuming stands are successfully regenerated (see section 2). Over the longer term, however, outcomes are much more uncertain.

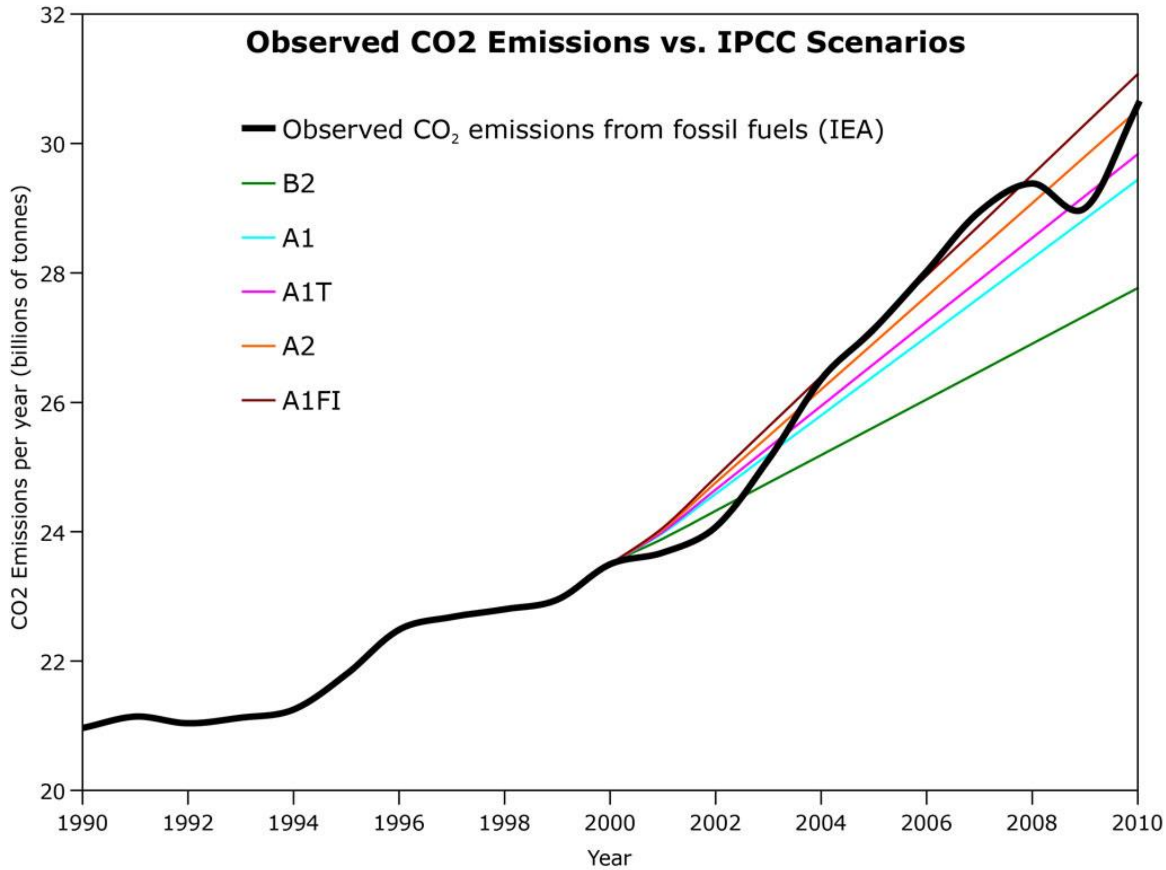

Figure 16. IEA global human CO_2 annual emissions from fossil fuels estimates versus IPCC SRES scenario projections.
The IPCC Scenarios are based on observed CO_2 emissions until 2000, at which point the projections take effect. Graph is available at http://www.skepticalscience.com/news.php?n=779 [Last accessed May 3, 2013].

Significant reductions in productivity capacity due to reduced survival threaten to destabilize ecosystems beyond their resilient capacity. As Welham (2013) has pointed out, traditional resource management is concerned with the question of to what extent the self-organizing capabilities of an ecosystem can be perturbed and still achieve desired outcomes. With reclamation, in contrast, the question is how much of the self-organization capabilities of a system must be created to achieve desired outcomes. One feature that would serve to promote resilience by avoiding drought stress is to ensure the rooting zone possesses adequate available water holding capacity. This can be accomplished by ensuring capping materials have higher organic matter content, are not predominantly coarse textured, and of sufficient depth (see Alberta Environment 2006, for further guidance). Layering of capping materials to generate textural breaks also serves to increase moisture storage, at least temporarily (Alberta Environment 2006). Another important feature in creating resilience is to make sure species are properly matched to edatopic position. Aspen, and particularly spruce, occupy wetter positions on the edatopic grid. For the most part, these species are more prone to drought than pine (Figure 12). It is important then to ensure they are not planted on sites that may be marginal in terms of available moisture. This includes salt-affected sites that may be present around toe slope drainage areas.

In that respect, another consideration is to actively modify planting prescriptions in anticipation of a drier climate. Conceptually, this approach is based on the assumption a given soil moisture regime (i.e., as positioned on the edatopic grid; see Beckingham and Archibald 1996) will for all intents and purposes transition to a drier edatopic position with further climate warming. Grasses rather than pine, for example, may dominate xeric sites, while aspen and spruce distribution could be relegated to what is presently deemed a wetter edatopic position.

In Europe, mitigative activities against climate change at the stand level are focusing on the regeneration phase (Keenan 2012). One approach is to increase the genetic or species diversity in seeded and planted stands. Over several centuries, tree-breeding programs (termed provenance trials) have been employed worldwide to acquire desirable traits. The same techniques can be applied in oil sands reclamation to develop the right suite of attributes of forest tree populations for future climates such as higher temperature and drought tolerance, and capacity to take advantage of increased levels of atmospheric CO_2 (see Alberto et al. 2013, for a review). Additionally, molecular genetics techniques have been developed that significantly reduce the time and resources needed for the selection process (see El-Kassaby and Lstibůrek 2009). This approach clearly has associated risks because of the high uncertainties in projections of future climate at local and regional scales. The right forest composition for future conditions is also likely to be sub-optimal for current conditions meaning there must be trade-offs in suitability for current and future climates. Other possible silvicultural measures to promote establishment and maintenance of desired communities include moving up the planting season to take advantage of earlier spring conditions, using containerized stock to reduce drought risk and reduced spacing to increase recovery after dry periods.

3.3 Final Thoughts

The recent worldwide increase of drought-related tree mortality (reviewed by Allen et al. 2009) has triggered an interest in determining the exact mechanisms by which death occurs (McDowell et al. 2008). In addition to direct causation, biotic factors such as pathogens and insects can amplify the negative effects of drought. The biotic agent demographics hypothesis suggests that drought drives changes in demographics of mortality agents (e.g., insects and pathogens) that subsequently drive forest mortality. Potential demographic changes include increased number of pathogen generations per year as a result of longer growing seasons, or decreased over-winter mortality because of warmer winter minimum temperatures. Biotic agents may amplify, or be amplified by, plant physiological stress (McDowell et al. 2008). Hogg et al. (2005) hypothesized that the magnitude of aspen mortality could have been exacerbated by the presence of defoliators. The widespread Mountain Pine Beetle epidemic in British Columbia and the western US that destroyed millions of hectares of Lodgepole pine is partly a consequence of unseasonably warm winters (Powell and Bentz 2009). FORECAST Climate provides an index of moisture stress but it did not include an evaluation of how that stress might impact insect and pathogens as mortality agents. This can be done, however. For example, FORECAST output has been integrated within an insect infestation model to simulate the population dynamics of spruce weevil (Schwab et al. 2011) and Mountain Pine Beetle (Welham unpublished) on stand survival and productivity.

Quantitative models, such as FORECAST Climate, can project forest responses and the goods and services those forests provide for a range of future climate change scenarios. At this point, unfortunately, no model is capable of predicting the future with the level of accuracy and precision needed by resource managers and by extension, reclamation practitioners (Pilkey and Pilkey-Jarvis 2007). In this context, model projections should not be used as a prediction of future outcomes but rather to narrow the range of plausible outcomes, identify the range of uncertainty, and suggest appropriate management actions and alternatives (Littell et al. 2011). FORECAST Climate then serves as guidance tool to help inform the decision-making process. As Subedi and Sharma (2013) point out, predictions made using these climate-based models need to inform best management practices and can be coupled to the continuous learning that forms the basis of an adaptive management process, thereby reducing the uncertainty associated with reclamation decisions. To this end it is important to monitor the climate through precipitation and temperature changes to assess which climate change prediction/scenario the environment is tracking most closely in order to understand better what the future climate holds.

4 CONCLUSIONS AND RECOMMENDATIONS

The following sections provide conclusions and recommendations for each of the objectives of the Phase III work.

4.1 Model Projections of Plant Regeneration Under Climate Change on Actual Oil Sands Reclamation Materials

Conclusion 1: Regeneration probabilities for two natural sites were lower than the corresponding moisture regimes on reclaimed sites. The discrepancies were largely a consequence of differences in their physical properties (in particular, percolation rates).

Recommendation 1: Soil moisture regime needs to be assessed carefully using a suite of metrics to ensure that soil properties between natural and reclaimed sites are truly analogous.

Conclusion 2:

A. From a reclamation perspective, the impact of climate change on regeneration requires careful consideration of the tree species and its associated moisture regime.

B. Soil moisture regime generated pronounced differences in regeneration probabilities both within a given future time period, and across periods.

C. Regeneration was highest in the wettest moisture regime and declined as the moisture regime became drier.

D. The difference between moisture regimes within a given time period also increased over time for all species.

E. Drier regimes (subxeric and xeric) appear to introduce a substantially greater average risk that revegetation success in a future climate may be compromised through regeneration failure.

Recommendation 2: Soil prescriptions should be developed and/or applied which generate moisture regimes that are submesic and wetter.

Conclusion 3: No single set of reclamation prescriptions will be adequate to maintain the current suite of tree species common to the region.

Recommendation 3:

A. Current one-layer prescriptions seem adequate for maintaining pine and aspen regeneration through the next century, or so.

B. Practices governing spruce should transition over the next several decades towards an emphasis on constructing two-layer prescriptions only, in an effort to minimize the risk of inadequate regeneration.

C. Drier sites should be focused on pine and possible aspen regeneration, with spruce on wetter sites.

Conclusion 4:

A. Reclamation practices that generate the two wettest moisture regimes (mesic and subhygric) are most likely to result in successful outcomes, at least through the 2050s.

B. Drier moisture regimes tend to have lower regeneration probabilities. Results were highly variable across the climate scenarios, however.

C. From a management perspective, constructing covers that result in drier moisture regimes introduces uncertainty in outcome and thus considerably more risk of inadequate regeneration.

D. Although regeneration was also high in the 2080s, for many moisture regimes uncertainty in model predictions was also high.

Recommendation 4:

A. Soil covers that favor wetter moisture regimes should be constructed preferentially, and phased in to cover design criteria. This will reduce the risk of regeneration failure, particularly as the climate continues to warm.

4.2 Analysis of Risks to Ecosystem Productivity From Climate Change Using FORECAST Climate

Conclusion 5:

A. Within a given species, the highest mortality almost always occurred under the A1FI emissions scenario. Though A1FI was considered a pessimistic outcome in terms of CO_2 emissions, current evidence indicates that, in fact, it may be close to reality.

B. For a given mortality rate, pine and spruce appear generally robust to drought conditions at least over the next several decades, regardless of the climate regime. Mortality tended to increase thereafter as the simulation years got longer (i.e., later in the century).

C. Aspen showed a small increase in mortality over time beginning in the first decade of the simulations, indicating the relative sensitivity of this species to climate conditions.

D. Significant reductions in productive capacity from climate-driven mortality threaten to destabilize ecosystems beyond their resilient capacity.

E. When species were robust to moisture stress, volume production under climate change was predicted to always exceed that projected under the historical climate regime. If species were less tolerant of moisture stress, climate change will have a negative impact on stand-level productivity later in the century, though how much depends on the species (e.g., little effect in pine, neutral in aspen, and negative in spruce).

Recommendation 5:

A. Avoid drought and promote resilience by ensuring the rooting zone possesses adequate available water holding capacity. This can be accomplished by ensuring capping materials have higher organic matter content, are not predominantly coarse textured, and are of sufficient depth. Layering of capping materials to generate textural breaks also serves to increase moisture storage, at least temporarily.

B. Properly match tree species to their edatopic position. Aspen, and particularly spruce, occupy wetter positions on the edatopic grid. For the most part, these species are more prone to drought than pine. It is important then to ensure they are not planted on sites that may become marginal in terms of available moisture.

C. Actively modify planting prescriptions in anticipation of a drier climate. Conceptually, this approach is based on the assumption a given soil moisture regime will, for all intents and purposes, transition to a drier edatopic position with further climate warming.

D. Increase the genetic or species diversity in seeded and planted stands. This can be accomplished with traditional tree-breeding programs (termed provenance trials) though molecular genetics techniques have been developed that significantly reduce the time and resources needed for the selection process.

E. Other silvicultural measures to promote establishment and maintenance of desired communities include moving up the planting season (to take advantage of earlier spring conditions), using containerized stock to reduce drought risk and reduced spacing to increase recovery after dry periods.

5 NEXT STEPS

The overall project was conceived as utilizing a phased approach. Each phase is sequential such that its results and conclusions represent the foundation for subsequent work. In that respect, further developments could include one or more of: (1) a spatially explicit analysis of habitat development in conjunction with progressive reclamation objectives, (2) a photorealistic visual representation of mine reclamation with underlying data layers calibrated from model output, and (3) an evaluation and analysis of the efficacy of reclamation practices in conferring ecosystem resilience, given uncertainties in climate change.

5.1 Habitat Suitability: A Spatial Analysis

In Phase I, a habitat suitability analysis was conducted for 10 wildlife species. Habitat suitability indices (HSIs) were calculated from EIA projections of the cumulative area reclaimed to a given ecosite type on the Kearl Lake mine footprint but did not include parameters that required spatially explicit metrics. Many of the habitat suitability equations contain a component that accounts for the spatial proximity of potential disturbance agents (roads and permanent structures, for example). Disturbances within specified zones of influence have a negative effect upon habitat suitability, and can decrement a given index by as much 50%. Zones of influence are species-specific and vary from distances < 50 m (northern goshawk) to < 1,000 m (moose). Much of progressive reclamation is anticipated to occur when mining operations are still being conducted which suggests that disturbance will be an ongoing issue on the mine footprint. Furthermore, it seems likely that at least some permanent structures (roads, for example) will remain active following mine closure to provide access for ongoing maintenance and monitoring, and to enhance recreational opportunities for local communities. This suggests a tradeoff between access requirements and habitat integrity. An understanding of these relationships could thus better inform the process of closure planning and in designing closure plans to mitigate negative impacts.

The proposed approach is to develop a spatially explicit, interactive platform to allow for calculation of the spatial metrics and illustrate habitat development within a three-dimensional simulated reclaimed landscape. Alberta Environment has already created the basic GIS layers that can be used as the base-mapping platform. This platform will be overlain with additional GIS layers that represent projected ecosite development (from the EIA documents) and associated HSIs, recalculated after accounting for spatial proximity. One objective is to create a visual portrayal to stakeholders of how wildlife habitat might be expected to develop on the mine footprint. A second objective is to create an interactive tool such that stakeholders are provided with a 3-dimensional portrayal of habitat development that can be viewed from different aspects and altitudes, and in conjunction with progressive reclamation.

The change in habitat suitability for a given species will be summarized for the no-mining condition (i.e., as if mining had not occurred at Kearl Lake) and for the active mine footprint, the latter as (a) reclamation proceeds in a progressive manner towards mine closure, and (b) the habitat attributes for a given analysis unit change in relation to stand development. Comparison of ‘no mining’ versus ‘active’ mining provides an assessment of the relative impact of mine development on habitat and will contribute to regional assessments of the risk oil sands mining poses to the viability of healthy wildlife populations. Projecting the temporal trends in habitat recovery is an important metric for evaluating the rate at which progressive reclamation can contribute to the overall pool of available habitat. For example, results from the Phase I analysis indicated that for most species (9/10), available habitat did not recover to level equivalent to the ‘no-mining’ condition until at least 55 years had elapsed following initial mine development. This, despite the fact these results constitute a ‘best case’ scenario because they were based solely on the development of structural attributes and did not account for the negative impact of climate change or the effect of disturbance.

5.2 Visualization Progressive Reclamation

Humans make profound judgements about the condition and desirability of their environment on the basis of visual impressions. The forest industry is a case in point. Environmental groups galvanized public opinion against industry practices by utilizing the various media outlets to transmit striking visual images of ‘poor’ practices (see, for example, Figure 17, left). Industry and government response was to focus on the legislated requirements for maintaining ecological integrity and supporting scientific evidence. This strategy held little sway over a public whose opinions were based on emotion rather than logic. A similar situation may be developing in the Alberta oil sands. Reclamation planning involves long-range projections of forest development under circumstances that can be complex and difficult for the layperson to easily comprehend. Images of landscapes denuded by mining have been disseminated widely in the media to great effect (see Figure 17, right) and few media reports are of a positive nature. As a result, public skepticism around mining practices is increasing and yet the industry has invested little effort in portraying their vision of how successful reclamation can revitalize the future landscape.

There is evidence that computer-based visualization tools can be effective in shaping public perceptions and enhancing the discourse around issues of appropriate resource management practices (for example, Sheppard and Meitner 2001). Important considerations in using visualization as a communication tool are to ensure the synthesized images are of high quality and possess good graphic realism (termed representational reality; Daniel and Meitner 2001). Another component is to ensure that the visual imagery is based on a solid ecological foundation. Virtual technology has developed to the point where photo-realistic images can be created *de novo* with minimal technical skill and computer resources. The risk is that any variability or unreliability in the visualizations has the potential to mislead the viewer and create unrealistic expectations (Sheppard 2001). Our objective is to create time sequences of visually realistic images based upon patterns of development in reclaimed ecosystems simulated by FORECAST Climate.

Figure 17. Visual depictions of logging activities (left – image from the Wilderness Committee) and oil sands mining (right – image from Greenpeace) as used to galvanize public opinion against industrial activities.

The technological and software requirements for this type of interactive visual engagement are becoming increasingly accessible, with development costs declining accordingly. Google, as part of their Google Earth Outreach program, for example is heavily promoting this type of visualization modeling. A ‘movie’ can be created of progressive reclamation using Google Earth as the GIS platform. The movie can be stopped at any time and the user can then navigate throughout the landscape. The movie can then be resumed from its point of departure.

A movie will be created of stand development on a subset of the Kearl Lake mine footprint using either AESRD’s basic GIS layers as the base-mapping platform or Google Earth. The reclaimed landscape will be populated according to the ecosite types and progressive reclamation plan derived from the Kearl Lake EIA documents (and used in the Phases I and II analyses), in conjunction with rates of stand development as projected by the FORECAST model in the previous phases of this project. A time slide will be added to the visual tool that will allow for the option of a temporal representation of stand development. Our expectation is that subsequent development of a full visualization tool (its expansion to include the entire mine footprint, as well as adding specific features to generate a more realistic post-mining landscape) will occur thereafter, after soliciting and incorporating input and opinion from Alberta Environment, OSRIN, and invited stakeholders, on the prototype example proposed here.

5.3 Evaluating the Resilience of Reclaimed Ecosystems

In a recent report, Welham (2013) reviewed the basic concepts and application of resilience in ecology and argued that this paradigm should be an integral part of reclamation. One challenge to its implementation is that resilience is an emergent property of ecosystems, an outcome of their inherent capacity for self-organization (the interaction between structure and process that leads to system development). As such, complex systems such as reclaimed plant communities cannot be 'deconstructed' with a view to managing the behavior of each (simplified) part in isolation; in systems with a capacity for emergent behavior, the whole will become by definition something else than the sum of its parts (Solé and Bascompte 2006)[7]. This paradigm is in contrast to the classic reductionist approach to ecology which focuses on each component in isolation (Puettmann et al. 2013), and which underlies much of current reclamation planning and practice.

There are two basic definitions for resilience. Engineering resilience refers to the length of time that a system takes to return to equilibrium following perturbation (i.e., disturbance) (Pimm 1984). Holling (1973) introduced a variation on this theme and defined 'ecological' resilience as the amount of perturbation a system can withstand before it moves into a different basin of attraction or stability domain (see Welham 2013, for further details).

Resilience in natural and reclaimed ecosystems are mirror images. Applying the concept to management of 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?" (Welham 2013). In this respect, one application of the definition of engineering resilience is to use process rates and patterns of development from (resilient) natural forested ecosystems in the region as a benchmark. If one considers reclamation as an effort at restoring ecosystem function with the goal of realizing end land-use objectives then the engineering resilience of reclaimed systems could be evaluated with respect to the extent to which these patterns and rates are congruent. Several metrics in the current version of the CEMA Revegetation Manual (indicator species, similarity indices; Alberta Environment 2010) suggest the utility of this approach has been recognized though only in a limited way and not within the context of resilience. Our proposal is to employ a modeling approach and conduct a comparative analysis between natural (young fire-disturbed and mature undisturbed) sites and reclaimed sites across a broad set of metrics, such as peat versus litter-based nutrient cycling (DeAngelis 1980), productivity and biomass accumulation (both overstory and understory; Pimm 1984), available moisture (and its countermeasure, moisture stress), and mortality rates. The

[7] 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.

intent is to determine the extent to which these metrics differ, and whether their trajectories converge and over what time scale. The basic question in this aspect of the project is *when does a reclaimed system achieve an equivalent resilient capacity to a natural system (or not)*? The answer has a direct bearing on the time frame used to define equivalent capability[8] and when a reclamation certificate could be granted with confidence that end land-use objectives will be realized.

While the previous analysis informs the development of engineering resilience, from the perspective of ecological resilience a critical question is *how does one determine that a reclaimed system has indeed moved into a different stability domain*? This has important implications for assessing equivalent capability and achieving land-use objectives. Model simulations, for example, indicate that climate change will impact tree survival and productivity in natural (Welham and Seely 2011) and reclaimed sites (this report). These changes will affect other components of the ecosystem, such as understory dynamics, nutrient cycling, and moisture demand. When are these changes sufficient to define a change in state, i.e., when has the resilience capacity of the ecosystem been exceeded such that desired end land-use objectives will not be achieved, and/or the system has switched to a different ecosite type? Given that natural systems will also be impacted by climate change, how do anticipated changes in reclaimed systems compare and differ from natural sites? Does the definition of equivalent capability depend on a benchmark established under historical climate conditions? Supposing the future capabilities of natural systems are altered, then should that not constitute the appropriate equivalence baseline? To address these questions a series of model simulations will be conducted that contrast natural and reclaimed ecosystems, as listed in Table 9.

Table 9. List of simulation runs that will be conducted on natural (N) and equivalent reclaimed (R) ecosystems under historical (h) and a series of future (f) climate scenarios.

Comparison	**Rationale**
N (h) vs. R (h)	What is the impact of historical climate on ecosystem processes associated with natural and reclaimed ecosystems? Do natural and reclaimed sites differ significantly under historical climate conditions? How are these differences evaluated from the perspective of engineering and ecological resilience?
N (h) vs. N (f)	How much will natural sites be affected by climate change? Are these differences significant?

[8] Equivalent land capability means that the ability of the land to support various land uses after conservation and reclamation is similar to the ability that existed prior to an activity being conducted on the land, but that the individual land uses will not necessarily be identical (*Conservation and Reclamation Regulation*, EPEA).

Comparison	Rationale
R (h) vs. R (f)	How much will reclaimed sites be affected by climate change? Are these differences significant?
N (f) vs. R (f)	Do natural and reclaimed sites differ significantly under future climate conditions? How does this compare with historical climate conditions?

Statistical methods will be employed (see Blanco et al. 2007, Blanco and Gonzalez 2010, Lo et al. 2011, for examples) that specify the relative similarity in model outcomes among the contrasts listed in Table 9. Using a range of thresholds to specify distinctiveness among contrasts (for a given ecosystem property), it will be possible to establish when resilient capacity has been exceeded. As with many issues in reclamation, no single threshold or property can provide the definitive answer. Rather, our primary intent is to highlight the various means by which resilience in reclaimed ecosystems can be defined. It should also be possible, however, to develop a hierarchy of decision 'nodes' to rank the different ecosystem properties in terms of their relative impact on resilience and long-term outcomes. This approach has similarities, for example, to the hierarchical approach used in Alberta to classify ecosystem types. It begins with a cover type description and then refines the classification using understory features (see Beckingham and Archibald 1996). The difference here is that we will define the criteria by which one ecosystem-type transitions to another when its resilience capacity is exceeded. At the very least, this analysis will provide the basis for a meaningful discussion of different options for defining resilience in reclaimed ecosystems, and serve as a guide to subsequent development of best management practices. It can also be used as the basis for calibrating landscape-level models to predict transitions among ecosystem types under climate change.

6 REFERENCES

Alberta Environment, 2006. Land capability classification system for forest ecosystems in the oil sands, 3rd edition. Volume 1: Field manual for land capability determination. Prepared by the Cumulative Environmental Management Association, Fort McMurray, Alberta for Alberta Environment. Pub. No. T/875. 53 pp. plus appendices. http://environment.gov.ab.ca/info/library/7707.pdf [Last accessed May 13, 2013].

Alberta Environment, 2010. Guidelines for reclamation to forest vegetation in the Athabasca oil sands region, 2nd Edition. Prepared by the Terrestrial Subgroup of the Reclamation Working Group of the Cumulative Environmental Management Association, Fort McMurray, Alberta. 332 pp. http://environment.gov.ab.ca/info/library/8269.pdf.

Alberto, A.F., S.N. Aitken, R. Alía, S.C. Gonzáliz-Martínez, H. Hänninen, A. Kremer, F. Lefèbvre, T. Lonormand, S. Yeaman, R. Whetten and O. Savolainen, 2013. Potential for evolutionary responses to climate change – evidence from tree populations. Global Change Biology 19: 1645-1661.

Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears and E.H. Hogg, 2009. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management. doi: 10.1016/j.foreco.2009.09.001

Audet, P., S. Arnold, A.M. Lechner, D.R. Mulligan and T. Baumgart, 2012. Climate suitability estimates offer insight into fundamental revegetation challenges among post-mining rehabilitated landscapes in eastern Australia. Biogeosciences Discussions 9: 18545-18569. doi:10.5194/bgd-9-18545-2012.

Barber, V.A., G.P. Juday and B.P. Finney, 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature (London) 405: 668-673.

Barrow, E. and G. Yu, 2005. Climate scenarios for Alberta. Report Prepared for the Prairie Adaptation Research Collaborative (PARC) in co-operation with Alberta Environment. PARC, University of Regina, Regina, Saskatchewan. http://www.parc.ca/pdf/Alberta_Scenarios/main_report.pdf [Last accessed September 16, 2011].

Beckingham, J.D. and J.H. Archibald, 1996. Field guide to ecosites of northern Alberta. Canadian Forest Service, Northwest Region, Northern Forestry Centre, Edmonton, Alberta. Special Report 5.

Bi, J., J.A. Blanco, J.P Kimmins, Y. Ding, B. Seely and C. Welham, 2007. Yield decline in Chinese Fir plantations: A simulation investigation with implications for model complexity. Canadian Journal of Forest Research 37: 1615-1630.

Blanco, J.A., and E. González. 2010. Exploring the sustainability of current management prescriptions for *Pinus caribaea* plantations in Cuba: a modelling approach. Journal of Tropical Forest Science 22: 139–154.

Blanco J.A., B. Seely, C. Welham, J.P Kimmins and T.M. Seebacher, 2007. Testing the performance of FORECAST, a forest ecosystem model, against 29 years of field data in a Pseudotsuga menziesii plantation. Canadian Journal of Forest Research 37: 1808-1820.

Cannell, M.G.R. and R.I. Smith, 1986. Climatic warming, spring budburst and frost damage on trees. Journal of Applied Ecology 23: 177-191.

Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L.C. Irland, A.E. Lugo, C.J. Peterson, D. Simberloff, F.J. Swanson, B.J. Stocks and B.M. Wotton, 2001. Climate change and forest disturbances. Bioscience 51(9): 723-734. http://flux.aos.wisc.edu/~adesai/documents/macrosys_papers-ankur/disturbance/Dale-Bioscience-Climatedisturbance.pdf [Last accessed May 13, 2013].

Daniel J. and M. Meitner, 2001. Representational validity of landscape visualizations: the effects of graphical realism on perceived scenic beauty of forest vistas. Journal of Environmental Psychology 21: 61-72.

Daniels, L.D., T.B. Maertensa, A.B. Stana, S.P.J. McCloskey, J.D. Cochrane and R.W. Gray, 2011. Direct and indirect impacts of climate change on forests: three case studies from British Columbia. Canadian Journal of Plant Pathology 33: 108-116.

DeAngelis, D.L., 1980. Energy flow, nutrient cycling, and ecosystem resilience. Ecology 61: 764-771.

El-Kassaby, Y.A. and M. Lstibůrek, 2009. Breeding without breeding. Genetic Research 91: 111-120.

Franklin, J.F., F.J. Swanson, M.E. Harmon, D.A. Perry, T.A. Spies, V.H. Dale, A. Mckee, W.K. Ferrell, J.E. Means, S.V. Gregory, J.D. Lattin, T.D. Schowalter and D. Larsen, 1992. Effects of global climate change on forests of northwest North America. IN: Peters, R.L. and J.E. Lovejoy (Eds.), Global Warming and Biological Diversity. Yale University Press, New Haven, Connecticut. pp. 244-257.

Fritts, H.C. 1976. Tree rings and climate. Academic Press, London, U.K.

Fuchigama, L.H., C.J. Weiser, K. Kobayashi, R. Timmis and L.V. Gusta, 1982. A degree growth stage (◦GS) model and cold acclimation in temperate woody plants. IN: Li, P.H. and A. Sakai (Eds.). Plant Cold Hardiness and Freezing Stress, vol. 2. Academic Press, New York, USA. pp. 93-116.

Gylander T., A. Hamann, J.S. Brouard and B.R. Thomas, 2012. The Potential of Aspen Clonal Forestry in Alberta: Breeding Regions and Estimates of Genetic Gain from Selection. PLoS ONE 7(8): e44303. doi:10.1371/journal.pone.0044303

He, H.S., D.J. Mladenoff and T.R. Crow, 1999. Linking an ecosystem model and a landscape model to study forest species response to climate warming. Ecological Modelling 114: 213-233.

Hogg, E.H., J.P. Brandt and B. Kochtubajda, 2002. Growth and dieback of aspen forests in northwestern Alberta, Canada, in relation to climate and insects. Canadian Journal of Forest Research 32: 823–832.

Hogg, E.H., J.P. Brandt and B. Kochtubajda, 2005. Factors affecting interannual variation in growth of western Canadian aspen forests during 1951-2000. Canadian Journal of Forest Research 35: 610-622.

Hogg, E.H., J.P. Brandt and M. Michaelian, 2008. Impacts of a regional drought on the productivity, dieback, and biomass of western aspen forests. Canadian Journal of Forest Research 38: 1373-1384.

Hogg, E.H. and A.G. Schwarz, 1997. Regeneration of planted conifers across climatic moisture gradients on the Canadian prairies: Implications for distribution and climate change. Journal of Biogeography 24: 527-534.

Hogg, E.H. and R.W. Wein, 2005. Impacts of drought on forest growth and regeneration following fire in southwestern Yukon, Canada. Canadian Journal of Forest Research 35: 2141-2150.

Holling C.S. 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4: 1-23.

Keenan, R.J., 2012. Adaptation of Forests and Forest Management to Climate Change: An Editorial. Forests 3: 75-82.

Kellomaki, S., H. Peltola, T. Nuutinen, K.T. Korhonen and H. Strandman, 2008. Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. Philosophical Transactions of the Royal Society (London) B: 363: 2341-2351.

Kimmins, J.P., J.A. Blanco, B. Seely, C. Welham and K. Scoullar, 2010. Forecasting Forest Futures: A Hybrid Modelling Approach to the Assessment of Sustainability of Forest Ecosystems and their Values. Earthscan Ltd., London, UK.

Kimmins, J.P., D. Mailly and B. Seely, 1999. Modelling forest ecosystem net primary production: the hybrid simulation approach used in FORECAST. Ecological Modelling 122: 195-224.

Kozlowski, T. T. and S. G. Pallardy. 1997. Growth Control in Woody Plants. Academic Press, San Diego.

Littell J.S., D. McKenzie, B.K. Kerns, S. Cushman and C.G. Shaw, 2011. Managing uncertainty in climate-driven ecological models to inform adaptation to climate change. Ecosphere 2: 1-19.

Lo, Y-H., J.A. Blanco, B. Seely, C. Welham and J. P. (Hamish) Kimmins, 2011. Generating reliable meteorological data in mountainous areas with scarce presence of weather records: The performance of MTCLIM in interior British Columbia, Canada. Environmental Modelling & Software 26: 644-657.

Maini, J.S., 1968. Silvics and ecology of Populus in Canada. IN: Growth and utilization of poplars in Canada. J.S. Maini and J.H. Cayford, eds . Canadian Department of Forestry and Rural Development, Ottawa, Ontario. Publication 1206. pp. 20-69.

MacDonald, G.M., J. M. Szeicz, J. Claricoates, and K. A. Dale. 1998. Response of the Central Canadian Treeline to Recent Climatic Changes. Annals of the Association of American Geographers, 88: 183–208.

McDowell, N., W.T. Pockman, C.D. Allen, D.D. Breshears, N. Cobb, T. Kolb, J. Plaut, J. Sperry, A. West and D.G. Williams, 2008. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? New Phytologist 178: 719-739.

McGuire, A.D., R.W. Ruess, A. Lloyd, J. Yarie, J.S. Clein and G.P. Juday, 2010. Vulnerability of white spruce tree growth in interior Alaska in response to climate variability: dendrochronological, demographic, and experimental perspectives. Canadian Journal of Forest Research 40: 1197-1209.

McKenzie, D., D.W. Peterson, D.L. Peterson and P.E. Thornton, 2003. Climatic and biophysical controls on conifer species distributions in mountain forests of Washington State, USA. Journal of Biogeography 30: 1093-1108.

Michaelian, M., E. Hogg, R. Hall and E. Arsenault, 2011. Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. Global Change Biology 17: 2084-2094.

Nitschke, C.R., 2010. Tree And Climate Assessment Model User's Guide Version 2.0.

Nitschke, C.R. and J.L. Innes, 2008a. Integrating climate change into forest management in South-Central British Columbia: an assessment of landscape vulnerability and development of a climate-smart framework. Forest Ecology and Management 256: 313-327.

Nitschke, C.R. and J.L. Innes, 2008b. A tree and climate assessment tool for modelling ecosystem response to climate change. Ecological Modelling 210: 263-277.

Peterson, E.B. and N.M. Peterson, 1992. Ecology, management, and use of aspen and balsam poplar in the prairie provinces. Forestry Canada, Northwest Region, Northern Forest Research Centre, Edmonton, Alberta. Special Report 1.

Pilkey, O. and L. Pilkey-Jarvis, 2007. Useless Arithmetic: Why Environmental Scientists Can't Predict the Future. Columbia University Press, New York, New York.

Pimm, S.L., 1984. The complexity and stability of ecosystems. Nature 307: 321-326.

Powell, J.A. and B.J. Bentz, 2009. Connecting phenological predictions with population growth rates for mountain pine beetle, an outbreak insect. Landscape Ecology 24(5): 657-672.

Puettman, K.J., C. Messier and K.D. Coates, 2013. Managing forests as complex adaptive systems: introductory concepts and application. IN: *Managing Forests as Complex Adaptive Systems* (Messier, C., K.J. Puettmann and K.D. Coates, eds). Routledge, New York, New York. pp. 3-16.

Schwab, O., T. Maness, G. Bull, C. Welham, B. Seely, and J. Blanco. 2011. Modeling the timber supply impact of introducing weevil-resistant spruce in British Columbia with cellular automata. Forest Policy and Economics 13: 61–68.

Schwingruber, F.H., K.R. Briffa and P. Nogler, 1993. A Tree-Ring Densiometric Transect from Alaska to Labrador. Biometeorology 37: 151-169.

Seely, B., P. Arp and J.P. Kimmins, 1997. A forest hydrology submodel for simulating the effect of management and climate change on stand water stress. IN: Proceedings of IUFRO meeting Empirical and process-based models for forest tree and stand growth simulation, Oeiras, Portugal. pp. 463-477.

Seely, B., C. Hawkins, J.A. Blanco, C. Welham and J.P. Kimmins, 2008. Evaluation of a mechanistic approach to mixedwood modelling. The Forestry Chronicle 84(2): 181-193.

Seely, B. and C. Welham, 2010. Development and evaluation of an integrated modelling approach for a risk analysis of alternative reclamation strategies. Final Report project no. 2006-0029. Prepared for the Cumulative Environmental Management Association (CEMA), Fort McMurray, Alberta.

Seely, B., C. Welham and A. Elshorbagy, 2006. A comparison and needs assessment of hydrological models used to simulate water balance in oil sands reclamation covers. Report prepared for the Cumulative Environmental Management Association (CEMA), Fort McMurray, Alberta.

Sheppard, S. 2001. Guidance for crystal ball gazers: developing a code of ethics for landscape visualization. Landscape and Urban Planning 54: 183 – 199.

Sheppard, S., and M. Meitner. 2001. Using multi-criteria analysis and visualisation for sustainable forest management planning with stakeholder groups. For. Ecol. Manage. 207: 171 – 187.

Sokal, R., and F.J. Rohlf, 1981. Biometry. W.H. Freeman, New York, New York.

Solé, R. and J. Bascompte, 2006. Self-Organization in Complex Ecosystems. Princeton University Press, Princeton, New Jersey.

Subedi, N. and M. Sharma, 2013. Climate-diameter growth relationships of black spruce and jack pine trees in boreal Ontario, Canada. Global Change Biology 19: 505-516.

Szeicz, J.M., and G.M. MacDonald, 1996. A 930-year ring-width chronology from moisture-sensitive white spruce (*Picea glauca* Moench) in northwestern Canada. The Holocene 6: 345-351.

Urban, D.L., 1993. A User's Guide to ZELIG Version 2. Department of Forest Sciences, Colorado State University, Fort Collins, Colorado, USA.

van Mantgem, P.J., N.L. Stephenson, J.C. Byrne, L.D. Daniels, J.F. Franklin, P.Z. Fulé, M.E. Harmon, A.J. Larson, J.M. Smith, A.H. Taylor and T.T. Veblen, 2009. Widespread increase of tree mortality rates in the western United States. Science 323: 521-524.

Volney, W.J.A. and K.G. Hirsch, 2005. Disturbing forest disturbances. Forestry Chronicle 81: 662-668.

Welham, C., 2013. Factors Affecting Ecological Resilience of Reclaimed Oil Sands Uplands. Oil Sands Research and Information Network, University of Alberta, School of Energy and the Environment, Edmonton, Alberta. OSRIN Report No. TR-34. 44 pp. http://hdl.handle.net/10402/era.31714 [Last accessed June 21, 2013].

Welham, C. and B. Seely, 2011. Oil Sands Terrestrial Habitat and Risk Modelling for Disturbance and Reclamation – Phase II Report. Oil Sands Research and Information Network, University of Alberta, School of Energy and the Environment, Edmonton, Alberta. OSRIN Report No. TR-15. 93 pp. http://hdl.handle.net/10402/era.24547 [Last accessed May 13, 2013].

Wilmking, M., G.P. Juday, V.A. Barbier, and H.S.J. Zald, 2004. Recent climate warming forces contrasting growth responses of white spruce at treeline in Alaska through temperature thresholds. Global Change Biology 10: 1-13.

Yarranton, M. and G.A.Y. Yarranton, 1975. Demography of a jack pine stand. Canadian Journal of Botany 53: 310-314.

7 ACRONYMS

AWHC	Average Water Holding Capacity
CRI	Climate Response Index
CV	Coefficient of Variation
DRI	Decomposition Response Index
ForWaDy	Forest Water Dynamics
GCM	Global Circulation Model
GEM	Germination and Establishment Model
GSP	Growing Season Precipitation
MR	Moisture Regime
OSRIN	Oil Sands Research and Information Network
PCIC	Pacific Climate Impact Consortium
SEE	School of Energy and the Environment
SI	Site Index
SMR	Soil Moisture Regime
TACA	Tree and Climate Assessment
TDI	Transpiration Deficit Index

APPENDIX 1: Description of TACA

TACA analysis output predicts the response of trees in their regeneration niche to climate-driven phenological and biophysical variables (Figure A1; see Nitschke 2010 and Nitschke and Innes 2008 a,b for further details). TACA is therefore a vulnerability analysis tool that uses the following driving variables to determine the probability of species presence/absence:

- Growing degree-day thresholds;
- Species-specific threshold temperature;
- Minimum metabolic temperature;
- Chilling requirement;
- Bud break degree day threshold;
- Drought tolerance;
- Frost tolerance.

Minimum and maximum growing degree-day (GDD) thresholds are used to determine the lower and upper relationship between temperature and growth (Urban 1993). GDD are calculated by summing the number of degree-days above a species-specific baseline temperature for an entire year. If the GDD minimum threshold is not met or the maximum threshold is exceeded, it is assumed that the regeneration niche of a species has not been met, resulting in mortality (He et al. 1999) or preventing a species from becoming established (Dale et al. 2001, Franklin et al. 1992). It should be noted that the regeneration niche of a species is narrower than the realized niche of a mature tree and so this assumption does not necessarily preclude the presence of mature trees (McKenzie et al. 2003). Species-specific baseline temperatures are used to initiate physiological activity (Fuchigama et al. 1982). The accumulation of GDD occurs until a species-specific heat sum is reached, which then initiates bud break (Fuchigama et al. 1982). The timing of bud break is expected to occur at earlier dates due to climatic change, which may increase the risk of mortality by early spring frosts (Cannell and Smith 1986, Lavender 1989).

The probability of presence/absence is determined based on the average probability of a species meeting all phenological and biophysical criteria (see Figure A1) for a given climate scenario. A single climate scenario represents one year of weather. Multiple climate scenarios are run in TACA and are used to determine a species presence/absence probability under historic, current and/or future climatic scenarios. Future scenarios can be based on predictions from global circulation models or user-defined. A species must meet the GDD, chilling requirement, minimum temperature and drought parameters in a given scenario. If this is the case, its regeneration success is then potentially modified by the probability of frost damage. Frost damage is a product of the probability of frost events occurring multiplied by the frost modifier for a species (see Nitschke 2008 a,b, for examples). A species meeting all criteria receives a presence score of one and the climate conditions are assumed to be in the optimal range of the species' regeneration niche. A score of zero means that that species never satisfied the required parameters, and climate conditions were thus outside the regeneration niche. Probabilities between one and zero are a result of the suite of parameters being met in a proportion of the scenarios in combination with the probability of frost damage.

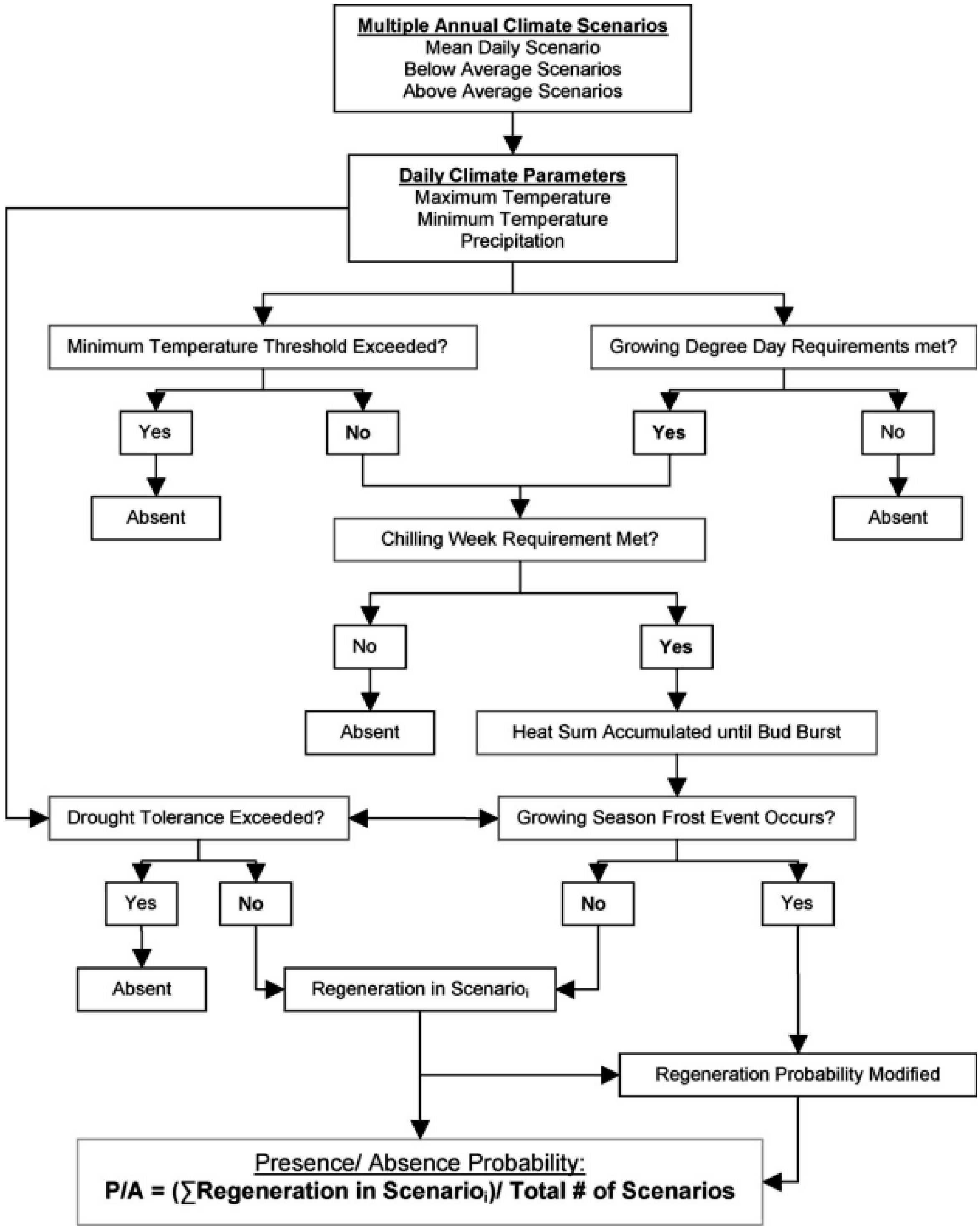

Figure A1. Diagram of model components and information flow in TACA (Nitschke 2010).

APPENDIX 2: TACA Calibration Data

TACA calibration data (see Nitschke 2010, Nitschke and Innes 2008 a,b, for definitions)

Species	Physiological Base Temperature (°C)	Heat Sum for Bud Burst (GDD)	Chilling Requirement (Days)	Minimum Temperature (°C)	Drought Tolerance	GDD Minimum	GDD Maximum	Frost Tolerance	Frost Season	Wet Soils
Trembling Aspen (seed)	3.5	189	70	-80	0.40	227	4414	0.9	300	0.30
Trembling Aspen (sucker)	3.5	189	60	-80	0.40	227	4414	0.95	320	0.30
White Spruce	2.7	147	42	-70	0.34	130	3459	0.9	305	0.50
Jack Pine	2.8	108	56	-85	0.42	250	4500	0.9	315	0.25

Species	Heat Moisture Index	Heat Sum (GDD)	Stratification (days)	Chilling X Heat Sum Factor	Germination Moisture Threshold	Min Temperature for Germination	Max Temperature for Germination	Vegetative Reproduction
Trembling Aspen (seed)	40	80	0	1.00	-0.80	3.5	32	1
Trembling Aspen (sucker)	45	80	0	1.00	-0.90	3.5	32	1
White Spruce	43.1	129	0	1.00	-0.50	2.7	35	0
Jack Pine	55	120	28	0.75	-0.90	2.8	30	0

Species	Low Nitrogen Availability	Medium Nitrogen Availability	High Nitrogen Availability	V.R. Type	Soil Temperature (°C)
Trembling Aspen (seed)	0.3	1	0.75	None	6
Trembling Aspen (sucker)	0.3	1	0.75	None	6
White Spruce	0.3	1	0.75	None	4
Jack Pine	0.85	1	0.2	None	6

	Moisture Regime				
Soil Parameters	Xeric	Subxeric	Submesic	Mesic	Subhygric
Soil Texture	S	LS	SL	SL	L
Soil Rooting Zone Depth (m)	0.6	0.65	0.65	0.89	0.75
Coarse Fragment %	0.24	0.2	0.31	0.38	0.3
AWSC mm/m of soil	154.6	192.3	290.0	290.0	362.5
Available Water Holding Capacity (mm)	70	100	130	160	190
Field Capacity mm/m	217.6	247.0	373.0	373.0	453.0
Available Field Capacity (mm)	99.2	128.4	167.3	205.8	237.8
Percolation (mm/day)	15.0	10.0	5.0	0.0	-5.0
Nitrogen Availability	2	1	1	1	3

	Site Name		
Soil Parameters	**Fort Chipewyan**	**Calling Lake**	**High Level**
Slope Position	Mid slope	Mid slope	Mid slope
Soil Texture	L	L	SL
Soil Rooting Zone Depth (m)	0.9	0.60	0.50
Coarse Fragment %	0.4	0.25	0.3
AWSC mm/m of soil	362.5	362.5	290.0
Available Water Holding Capacity (mm)	196	163	102
Field Capacity mm/m	453.0	453.0	373.0
Available Field Capacity (mm)	244.6	203.9	130.6
Percolation (mm/day)	15.0	16.0	13.0
Nitrogen Availability	2	1	1

Soil Property Table		
Soil Texture	**AWSC mm/m of soil**	**Field Capacity mm/m of soil**
Sand (S)	155	218
Loamy Sand (LS)	192	247
Sandy Loam (SL)	290	373
Fine Sandy Loam/ Sandy Clay Loam (FSL)	326	413
Loam and Silt Loam (L or SiL)	362	453
Clay Loam and Silty Clay Loam (CL,SiCL)	338	456
Silty Clay and Clay (SIC or C)	311	447
Organic (O)	368	587

APPENDIX 3: TACA Version Comparisons

A comparative analysis was undertaken of the older version of the Tree and Climate Assessment model (TACA 2011) used in the Phase II analysis and a newer version (TACA GEM; Germination and Establishment Model).

Aspen regeneration from seed had markedly lower probabilities than aspen regeneration from suckering, or spruce and pine seed regeneration (Figure A3.). Typically, TACA GEM projected lower regeneration probabilities than the original model. The addition of extreme events in TACA GEM generated the lowest regeneration probabilities, particularly for the 2050s and 2080s climate periods. This suggests that occurrence of extreme events is an important component in these types of models.

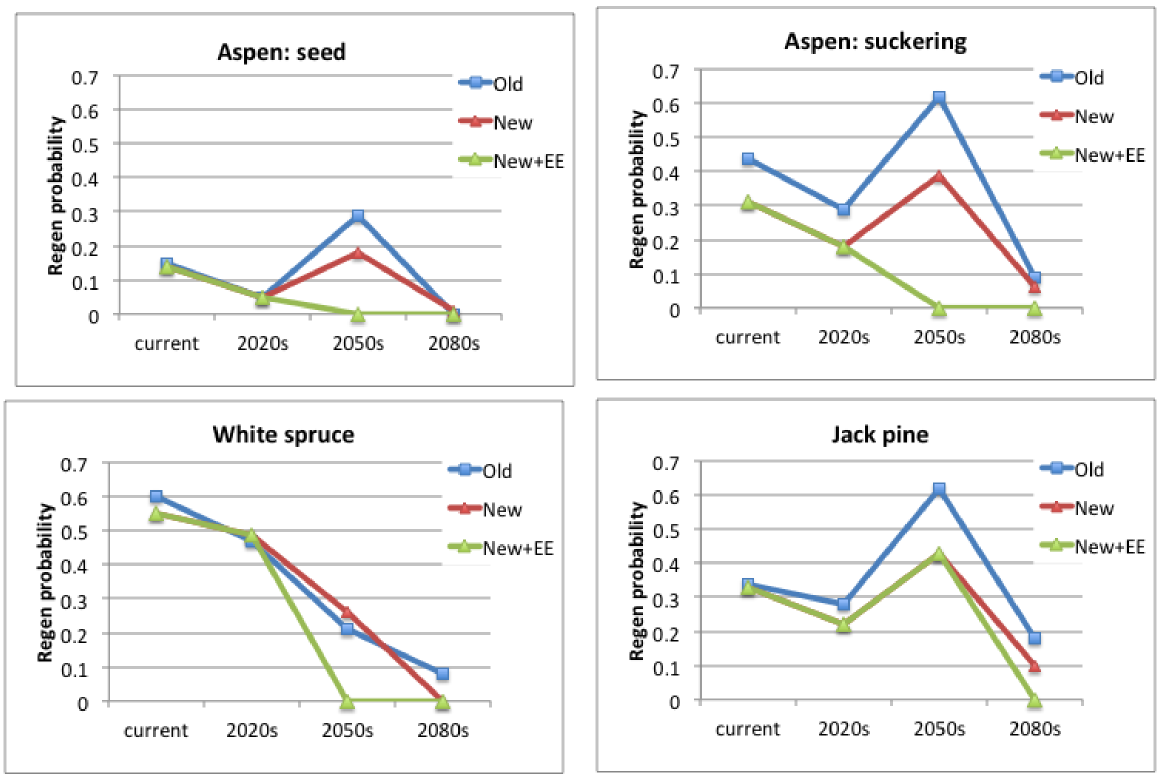

Figure A3. The probability of regeneration for aspen (from seed, and suckering), white spruce, and jack pine under climate conditions that are current and projected for the 2020-2050 (2020s), 2050-2080 (2050s), and 2080-2100 (2080s), in the High Level region of Alberta.
Results are derived from projections using the CCSRNIES global circulation model, with the A1F1 CO_2 emissions scenario (see Welham and Seely, 2011: Introduction, for reference details and from which further information can be derived).
Blue lines are probabilities projected under the TACA 2011 model, while red and green lines are projections from TACA GEM. The latter either excludes (red) or includes (green) extreme events.

LIST OF OSRIN REPORTS

OSRIN reports are available on the University of Alberta's Education & Research Archive at https://era.library.ualberta.ca/public/view/community/uuid:81b7dcc7-78f7-4adf-a703-6688b82090f5. The Technical Report (TR) series documents results of OSRIN funded projects. The Staff Reports (SR) series represent work done by OSRIN staff.

OSRIN Technical Reports – http://hdl.handle.net/10402/era.17507

BGC Engineering Inc., 2010. Oil Sands Tailings Technology Review. OSRIN Report No. TR-1. 136 pp. http://hdl.handle.net/10402/era.17555

BGC Engineering Inc., 2010. Review of Reclamation Options for Oil Sands Tailings Substrates. OSRIN Report No. TR-2. 59 pp. http://hdl.handle.net/10402/era.17547

Chapman, K.J. and S.B. Das, 2010. Survey of Albertans' Value Drivers Regarding Oil Sands Development and Reclamation. OSRIN Report TR-3. 13 pp. http://hdl.handle.net/10402/era.17584

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

Jones, R.K. and D. Forrest, 2010. Oil Sands Mining Reclamation Challenge Dialogue – Report. OSRIN Report No. TR-4A. 18 pp. http://hdl.handle.net/10402/era.19091

James, D.R. and T. Vold, 2010. Establishing a World Class Public Information and Reporting System for Ecosystems in the Oil Sands Region – Report and Appendices. OSRIN Report No. TR-5. 189 pp. http://hdl.handle.net/10402/era.19093

James, D.R. and T. Vold, 2010. Establishing a World Class Public Information and Reporting System for Ecosystems in the Oil Sands Region – Report. OSRIN Report No. TR-5A. 31 pp. http://hdl.handle.net/10402/era.19094

Lott, E.O. and R.K. Jones, 2010. Review of Four Major Environmental Effects Monitoring Programs in the Oil Sands Region. OSRIN Report No. TR-6. 114 pp. http://hdl.handle.net/10402/65.20287

Godwalt, C., P. Kotecha and C. Aumann, 2010. Oil Sands Tailings Management Project. OSRIN Report No. TR-7. 64 pp. http://hdl.handle.net/10402/era.22536

Welham, C., 2010. Oil Sands Terrestrial Habitat and Risk Modeling for Disturbance and Reclamation – Phase I Report. OSRIN Report No. TR-8. 109 pp. http://hdl.handle.net/10402/era.22567

Schneider, T., 2011. Accounting for Environmental Liabilities under International Financial Reporting Standards. OSRIN Report TR-9. 16 pp. http://hdl.handle.net/10402/era.22741

Davies, J. and B. Eaton, 2011. Community Level Physiological Profiling for Monitoring Oil Sands Impacts. OSRIN Report No. TR-10. 44 pp. http://hdl.handle.net/10402/era.22781

Hurndall, B.J., N.R. Morgenstern, A. Kupper and J. Sobkowicz, 2011. Report and Recommendations of the Task Force on Tree and Shrub Planting on Active Oil Sands Tailings Dams. OSRIN Report No. TR-11. 15 pp. http://hdl.handle.net/10402/era.22782

Gibson, J.J., S.J. Birks, M. Moncur, Y. Yi, K. Tattrie, S. Jasechko, K. Richardson, and P. Eby, 2011. Isotopic and Geochemical Tracers for Fingerprinting Process-Affected Waters in the Oil Sands Industry: A Pilot Study. OSRIN Report No. TR-12. 109 pp. http://hdl.handle.net/10402/era.23000

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

Kindzierski, W., J. Jin and M. Gamal El-Din, 2011. Plain Language Explanation of Human Health Risk Assessment. OSRIN Report TR-14. 37 pp. http://hdl.handle.net/10402/era.23487

Welham, C. and B. Seely, 2011. Oil Sands Terrestrial Habitat and Risk Modelling for Disturbance and Reclamation – Phase II Report. OSRIN Report No. TR-15. 93 pp. http://hdl.handle.net/10402/era.24547

Morton Sr., M., A. Mullick, J. Nelson and W. Thornton, 2011. Factors to Consider in Estimating Oil Sands Plant Decommissioning Costs. OSRIN Report No. TR-16. 62 pp. http://hdl.handle.net/10402/era.24630

Paskey, J. and G. Steward, 2012. The Alberta Oil Sands, Journalists, and Their Sources. OSRIN Report No. TR-17. 33 pp. http://hdl.handle.net/10402/era.25266

Cruz-Martinez, L. and J.E.G. Smits, 2012. Potential to Use Animals as Monitors of Ecosystem Health in the Oil Sands Region. OSRIN Report No. TR-18. 52 pp. http://hdl.handle.net/10402/era.25417

Hashisho, Z., C.C. Small and G. Morshed, 2012. Review of Technologies for the Characterization and Monitoring of VOCs, Reduced Sulphur Compounds and CH_4. OSRIN Report No. TR-19. 93 pp. http://hdl.handle.net/10402/era.25522

Kindzierski, W., J. Jin and M. Gamal El-Din, 2012. Review of Health Effects of Naphthenic Acids: Data Gaps and Implications for Understanding Human Health Risk. OSRIN Report No. TR-20. 43 pp. http://hdl.handle.net/10402/era.26060

Zhao, B., R. Currie and H. Mian, 2012. Catalogue of Analytical Methods for Naphthenic Acids Related to Oil Sands Operations. OSRIN Report No. TR-21. 65 pp. http://hdl.handle.net/10402/era.26792

Oil Sands Research and Information Network and Canadian Environmental Assessment Agency, 2012. Summary of the Oil Sands Groundwater – Surface Water Interactions Workshop. OSRIN Report No. TR-22. 125 pp. http://hdl.handle.net/10402/era.26831

Valera, E. and C.B. Powter, 2012. Implications of Changing Environmental Requirements on Oil Sands Royalties. OSRIN Report No. TR-23. 21 pp. http://hdl.handle.net/10402/era.27344

Dixon, R., M. Maier, A. Sandilya and T. Schneider, 2012. Qualifying Environmental Trusts as Financial Security for Oil Sands Reclamation Liabilities. OSRIN Report No. TR-24. 32 pp. http://hdl.handle.net/10402/era.28305

Creasey, R., 2012. Workshop on the Information that Professionals Would Look for in Mineable Oil Sands Reclamation Certification. OSRIN Report No. TR-25. 52 pp. http://hdl.handle.net/10402/era.28331

Alberta Innovates – Technology Futures, 2012. Investigating a Knowledge Exchange Network for the Reclamation Community. OSRIN Report No. TR-26. 42 pp. http://hdl.handle.net/10402/era.28407

Dixon, R.J., J. Kenney and A.C. Sandilya, 2012. Audit Protocol for the Mine Financial Security Program. OSRIN Report No. TR-27. 27 pp. http://hdl.handle.net/10402/era.28514

Davies, J., B. Eaton and D. Humphries, 2012. Microcosm Evaluation of Community Level Physiological Profiling in Oil Sands Process Affected Water. OSRIN Report No. TR-28. 33 pp. http://hdl.handle.net/10402/era.29322

Thibault, B., 2012. Assessing Corporate Certification as Impetus for Accurate Reporting in Self-Reported Financial Estimates Underlying Alberta's Mine Financial Security Program. OSRIN Report No. TR-29. 37 pp. http://hdl.handle.net/10402/era.29361

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

Pyper, M. and T. Vinge, 2013. A Visual Guide to Handling Woody Materials for Forested Land Reclamation. OSRIN Report No. TR-31. 10 pp. http://hdl.handle.net/10402/era.30381

Mian, H., N. Fassina, A. Mukherjee, A. Fair and C.B. Powter, 2013. Summary of 2013 Tailings Technology Development and Commercialization Workshop. OSRIN Report No. TR-32. 69 pp. http://hdl.handle.net/10402/era.31012

Howlett, M. and J. Craft, 2013. Application of Federal Legislation to Alberta's Mineable Oil Sands. OSRIN Report No. TR-33. 94 pp. http://hdl.handle.net/10402/era.31627

Welham, C., 2013. Factors Affecting Ecological Resilience of Reclaimed Oil Sands Uplands. OSRIN Report No. TR-34. 44 pp. http://hdl.handle.net/10402/era.31714

Naeth, M.A., S.R. Wilkinson, D.D. Mackenzie, H.A. Archibald and C.B. Powter, 2013. Potential of LFH Mineral Soil Mixes for Land Reclamation in Alberta. OSRIN Report No. TR-35. 64 pp. http://hdl.handle.net/10402/era.31855

OSRIN Videos – http://hdl.handle.net/10402/era.29304

Rooney Productions, 2012. Assessment Methods for Oil Sands Reclamation Marshes. OSRIN Video No. V-1. 20 minutes. Also available on the University of Alberta You Tube Channel (recommended approach).

Rooney Productions, 2012. Assessment Methods for Oil Sands Reclamation Marshes. OSRIN Video No. V-1. Nine-part mobile device version. Also available on the University of Alberta You Tube Channel (link to Part 1 - recommended approach).

OSRIN Staff Reports – http://hdl.handle.net/10402/era.19095

OSRIN, 2010. Glossary of Terms and Acronyms used in Oil Sands Mining, Processing and Environmental Management - January 2013 Update. OSRIN Report No. SR-1. 119 pp. http://hdl.handle.net/10402/era.17544

OSRIN, 2010. OSRIN Writer's Style Guide - December 2012 Update. OSRIN Report No. SR-2. 27 pp. http://hdl.handle.net/10402/era.17545

OSRIN, 2010. OSRIN Annual Report: 2009/2010. OSRIN Report No. SR-3. 27 pp. http://hdl.handle.net/10402/era.17546

OSRIN, 2010. Guide to OSRIN Research Grants and Services Agreements - June 2011 Update. OSRIN Report No. SR-4. 21 pp. http://hdl.handle.net/10402/era.17558

OSRIN, 2011. Summary of OSRIN Projects – June 2013 Update. OSRIN Report No. SR-5. 81 pp. http://hdl.handle.net/10402/era.20529

OSRIN, 2011. OSRIN Annual Report: 2010/11. OSRIN Report No. SR-6. 34 pp. http://hdl.handle.net/10402/era.23032

OSRIN, 2011. OSRIN's Design and Implementation Strategy. OSRIN Report No. SR-7. 10 pp. http://hdl.handle.net/10402/era.23574

OSRIN, 2012. OSRIN Annual Report: 2011/12. OSRIN Report No. SR-8. 25 pp. http://hdl.handle.net/10402/era.26715

OSRIN, 2013. OSRIN Annual Report: 2012/13. OSRIN Report No. SR-9. 56 pp. http://hdl.handle.net/10402/era.31211