Oil Sands Terrestrial Habitat and Risk Modeling for Disturbance and Reclamation – Phase I Report

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Oil Sands Research and Information Network

Oil Sands Research and Information Network

OSRIN is a university-based, independent organization that compiles, interprets and analyses available knowledge about returning landscapes and water impacted by oil sands mining to a natural state and gets that knowledge into the hands of those who can use it to drive breakthrough improvements in reclamation regulations and practices. OSRIN is a project of the University of Alberta's School of Energy and the Environment (SEE). OSRIN was launched with a start-up grant of $4.5 million from Alberta Environment and a $250,000 grant from the Canada School of Energy and Environment Ltd.

OSRIN provides:

- **Governments** with the independent, objective, credible information and analysis required to put appropriate regulatory and policy frameworks in place
- **Media, opinion leaders and the general public** with the facts about oil sands development, its environmental and social impacts, and landscape/water reclamation activities – so that public dialogue and policy is informed by solid evidence
- **Industry** with ready access to an integrated view of research that will help them make and execute reclamation plans – a view that crosses disciplines and organizational boundaries

OSRIN recognizes that much research has been done in these areas by a variety of players over 40 years of oil sands development. OSRIN synthesizes this collective knowledge and presents it in a form that allows others to use it to solve pressing problems. Where we identify knowledge gaps, we seek research partners to help fill them.

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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 will include an evaluation of the impact of disturbance (natural disturbance due to insect outbreaks, fire and wind, as well as other industrial and agricultural disturbances), conservation, and reclamation activities associated with oil sands development both at the lease and regional levels.

The project will be conducted in three phases. Each phase is sequential such that its results and conclusions represent the foundation for the subsequent work. In this way, project investment and outcomes can be realized incrementally. Four scenarios will be incorporated into the overall project. These include scenarios constituting a basecase analysis, climate change, mine development plans, and regional development plans. The basecase scenario is a series of outcomes derived with no consideration for future climate change. The importance of the basecase is that it represents the null condition and thus provides a context for comparing the relative impact of different climate change scenarios (the focus of subsequent project activities).

The basecase scenario was the main focus of the work conducted in Phase I, and is comprised of a dendrochronology study of the relationship between climate and tree growth in the sub-boreal region that encompasses oil sands mining, an aspatial analysis of habitat suitability for 10 wildlife species in relation to reclamation activities on the Kearl Lake mine, and a risk analysis of the potential for development of water stress in young reclamation plantations at the Kearl Lake mine. The report begins with an introductory chapter that defines core concepts and project objectives.

Dendrochronology

The dendrochronology work 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 review of on-line and literature sources was used to identify tree core collections from the region. A total of 29 chronologies were identified that matched a set of suitability criteria: 18 chronologies for white spruce, 8 for jack pine, 2 for black spruce and 1 for trembling aspen. In addition, 9 aspen chronologies were analyzed from cores collected within the region. Each core series was used to date tree rings by year of growth and to create master chronologies of ring width over the previous 75 years (1935 to 2009). Residual chronologies were generated by standardizing and detrending master chronologies to remove non-climate-related influences on growth. These residual chronologies were then correlated to one or more of 25 climate-related variables derived from climate records obtained from nearby weather stations. Results indicate that radial growth of white spruce was limited by current year water stress; significant relationships were found between radial growth and growing season precipitation and summer temperatures. Similar results were found for jack pine, but no conclusive results were found for trembling aspen or black spruce. Subsequent

work will be required to (a) add additional data sources, particularly for aspen, and (b) to determine whether additional climate relationships may better explain ring chronologies.

The full report is provided in Section 2.

Habitat suitability analysis

Habitat suitability indices (HSIs) were calculated from equations for 10 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. Input values for each index were derived from output generated from the ecosystem simulation model, FORECAST. The development of each index was calculated from the initiation of reclamation through to mine closure as per practices described in the Kearl Lake Environmental Impact Assessment (EIA). It should be noted that for some species, the HSI includes parameters with a spatial component, the latter of which requires calculation of one or more landscape metrics. For present purposes, HSIs were calculated for the 10 species without including spatial metrics. In practical terms, these HSIs then represent the most optimistic scenarios for habitat development since the inclusions of spatial metrics only serves to reduce habitat suitability (though in some cases, the HSI may remain unchanged).

Specific objectives were as follows:

- Review of habitat suitability models that may be applicable to Alberta boreal forests.
- Identify variables used in the habitat suitability models that can be simulated with the FORECAST model.
- Simulate the reclamation prescriptions described in the Kearl Lake EIA documents with FORECAST and generate output suitable for populating each habitat suitability model.
- Generate habitat suitability indices (HSIs) for 10 wildlife species (identified from the review) on the Kearl lake mine site and compare and contrast the temporal development of habitat from reclamation initiation to mine closure.

Conclusions were:

1. There is a 37-year window following mine operation when upland habitat suitability is very poor on the mine footprint (an area that encompasses almost 30,000 ha).
2. Habitat suitability recovers relatively quickly thereafter; 50 years after mine operation, 4 out of 10 species have a 100 % suitability index, and this increases to 9 out of 10 species 55 years after mine operation.
3. The overall quality and pattern of recovery in habitat suitability depends on how much upland is reclaimed relative to the original (pre-mining) landscape.

4. Deviations in the post-mining distribution of ecosite phases relative to the pre-mining landscape could have significant implications for the habitat suitability of particular species, either positively (more habitat is created) or negatively.
5. The broad variation among species in their HSI values suggests that reclamation practices could be targeted towards the habitat requirements of one particular wildlife species by preferentially reclaiming more favourable ecosite phases. Conversely, a broad range of ecosite phases is necessary to promote a higher degree of biodiversity on the reclaimed landscape.
6. When habitat recovery rates on reclaimed sites are considered in conjunction with the overall mine footprint, it suggests that the negative impact of the operation is not trivial with respect to habitat loss.

The full report is contained in Section 3.

A risk analysis of the potential development of water stress in young reclamation plantations

The development of ecologically viable reclamation strategies and methodologies in the oil sands region can be a difficult undertaking considering the logistical challenges of constructing soil covers capable of providing both the hydrological and nutritional characteristics required for the establishment of self-sustaining, productive forest ecosystems. To examine the potential for the development of water stress in proposed reclamation plantations within the Kearl Lake mining area, a risk analysis was conducted for different species and ecosite combinations using the stand-level forest hydrology model ForWaDy. The risk analysis was designed to evaluate the probability of high levels of water stress developing in young plantations of white spruce, trembling aspen, and jack pine established on different ecosites as a function of soil texture and slope position. Each species and soil type combination was simulated for a 25-year period using historical climate data from the Fort McMurray weather station. Annual summaries of simulated water stress (expressed as a Transpiration Deficit Index; TDI) during the growing season were used to derive probabilities of exceeding a range of water stress thresholds.

Spruce was the species most likely to experience high TDI levels (greater than 0.3). In addition, it was the only species to reach TDI levels greater than 0.6 during the 25-year simulation period. Jack pine, in contrast, was the least likely to experience high TDI levels and did not exceed levels of 0.5 during any year; the remaining species were intermediate between the spruce and pine. The probability of exceeding TDI thresholds was consistently greater in an a-b ecosite grouping (representing dry, nutrient poor sites) relative to a d-e grouping (moist, nutrient-rich sites). Differences between the two ecosite groupings were relatively small, however. The difference would have been greater if not for the 50 cm peat layer that is applied to each site as a rooting substrate, and which alone constitutes 70% to 80% of the water holding capacity of the total soil profile.

The probabilities reported here are based on the simulated response of the tree–soil combinations to the past 25 years of climate data (1982 - 2006). These years reflect the current climate but are not likely to be representative of future climate conditions predicted for the region from Global Circulation Models. An exploration of the impact of climate change on water stress and its implications for overall growth and the associated development of structural habitat elements will be conducted in Phase II of the project.

The full report is contained in Section 4.

The report concludes with a brief description of the next steps in the project.

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1 INTRODUCTION

A stated goal of Alberta Environment is to have effective risk management, preparation and responses to events and emerging and complex issues, supporting outcomes-based management and assuring Alberta's environment is safe, clean and sustained for future generations. In northeastern Alberta, oil sands mining is the single-most important economic activity in the region but it also constitutes a major disturbance to local ecosystems. One of the difficulties in implementing Alberta Environment's goal is that plans and reports associated with oil sands development have been evaluated principally on a case-by-case basis (i.e., with a focus on individual leases) and for discrete time periods (for example, the period of maximum mine activity and immediately after mine closure). The cumulative impacts of industrial operations on ecosystem function and services, attendant risks to terrestrial wildlife species, in conjunction with potential changes in the climatic regime, have not received adequate consideration. Recent and proposed expansion of the oil sands mining footprint make it imperative that potential impacts be considered over a variety of spatial and temporal scales. This requires the application of modeling tools to evaluate the impact of disturbance on ecosystem services and wildlife habitat, and whether these features can be recovered through reclamation activities, a key outcome from this project. Ultimately, the goal of this exercise is a decision support system to inform the relative risk to ecosystems of proposed and alternative development (and reclamation) trajectories within the context of potential climate change.

1.1 Climate Change: Its Potential Impact on Ecosystems

There is one overriding issue that must be addressed if the projections derived from a decision support tool are to be realistic. Over the past 50 years, regional climate patterns in Canada indicate a warming trend in southern and western regions (C-CIARN 2003). Long-term precipitation patterns have also changed with a trend towards drier summers and lower snowfall amounts (Environment Canada 2002). These patterns have been attributed largely to the rapid rise in atmospheric greenhouse gas (GHG) concentrations (particularly CO_2) over this period. Given that anthropogenic GHG emissions are increasing at higher than projected rates (Raupach et al. 2007), these climate trends will continue well into the future.

Changes in the climate regime could have a serious impact on ecosystem development (forest growth, tree species composition, and productivity), the goods and services they provide, and the wildlife species that depend on them. Longer, warmer summers may result in significantly less tree growth and productivity because prolonged periods of water stress reduce a tree's ability to photosynthesize (Kozlowski and Pallardy 1997), leading to reduced rates of cambial activity (Fritts 1976). Hogg et al. (2005) examined factors affecting variation in growth of western Canadian aspen forests during a fifty-year period. Most of the variation was explained by inter-annual variation in a climate moisture index in combination with insect defoliation. Results also indicated that severe drought may have triggered a major collapse in aspen productivity, while unusual, late winter thaw–freeze events were implicated as a major cause of forest dieback (see Hogg et al. 2002 and references therein). In addition to growth rates, recruitment success is also affected by climate. White and black spruce recruitment, for example, was directly correlated with fluctuations in summer temperatures (Macdonald et al. 1998). Recent evidence indicates a widespread increase in tree mortality rates through the western US, with regional warming and consequent increases in water deficits as likely contributors (van Mantgem et al. 2009).

1.2 Using Models that Represent Climate Change

The standard approach to projecting stand development is with models calibrated from empirical field data. The core assumption underlying this approach is that past production is a reasonable predictor of future production because conditions for growth will remain essentially unchanged. If the projected changes in climate are indeed realized, however, then the suitability of these relatively simple empirical models is highly questionable. This point is well illustrated by the work of Hogg et al. (2005); their study of climatic variation and insect defoliation demonstrated how quickly a change in growing conditions had impacted aspen growth and yield. One alternative is to develop models that predict a climate-growth response from parameters fitted using empirical data of climate in conjunction with an associated growth response (see, for example, Girardin et al. 2008). This type of empirical modeling approach captures the statistical relationship between growth and climate, but it provides no understanding of biological mechanisms and its predictive capacity is limited to the data range from which it was calibrated (see Girardin et al. 2008, for a more complete discussion). Process-based growth models, on the other hand, use physiological and physical principles in conjunction with simulated edaphic conditions to project forest development and productivity. 'Pure' process models tend to be more complex than their empirical counterparts (see Dixon et al. 1990, for examples), which often make their calibration difficult and inhibits portability. A practical compromise is the hybrid simulation (HS) approach. In an HS model, empirical data are used by the model to 'self-calibrate' at least some its ecosystem processes. This has the benefit of reducing the calibration load while ensuring simulated processes are linked directly to empirical measures (see below for a description of the FORECAST[1] Climate HS model). Regardless of the type of process model, their basic structure means that forest productivity is embedded within an environment that includes the simulation of climatic conditions. It is therefore possible to project the impacts of future climate scenarios on forest ecosystem development. Integrating climate-sensitive output into the decision support tool will improve its capacity to evaluate the relative risk of alternative management practices.

Applying a process model and generating credible output within the context of climate change is challenging. First, a reliable method must be employed for establishing the relationship between climatic factors and productivity. Typically, site-specific meteorological data are used to reconstruct the previous climate regime. Estimates of productivity are then derived and correlations established (see, for example, Girardin et al. 2008). At broad spatial scales, growth and productivity are a response to regional variations in temperature and precipitation patterns (Brubaker 1980, Cook and Cole 1991, Fritts 1974). In these cases, productivity estimates obtained from satellite data can be used to estimate forest production at regional to global scales

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[1] See http://www.forestry.ubc.ca/ecomodels/moddev/forecast/forecast.htm for background on FORECAST.

(Running et al. 2004). At finer spatial scales, climatic limiting factors and climate-growth relationships vary with differences in topographic position and soil properties (Ettl and Peterson 1995, Fritts 1974, Villalba et al. 1994). Furthermore, different species may respond differently to climate, even when growing on a common site either in isolation or in competition with one another (Colenutt and Luckman 1991, Graumlich 1993, Peterson and Peterson 1994, Villalba et al. 1994). At the local scale, field-based observations are a necessary requirement to document the impact of climate (see Boisvenue and Running 2006, for a review of these approaches).

1.3 Dendrochronology: A Useful Climate Metric

A variety of field-level climate-productivity metrics have been calculated (see Boisvenue and Running 2006). One metric that has been used extensively in climatic reconstructions is dendrochronology (Fritts 1976). By linking changes in ring width to climate, dendroclimatology has provided important insights into historical climate patterns. For example, the negative effects of water stress on tree ring patterns are well documented (Ettl and Peterson 1995, Peterson and Peterson 1994, 2001). In boreal forests, patterns in aspen ring chronologies were best explained by insect defoliation in conjunction with climatic factors (Hogg et al. 2002, 2005). Leonelli et al. (2008) found that aspen growth rings were more sensitive to climate on productive sites; ring widths were positively correlated with summer precipitation prior to the year of growth.

In an analysis conducted on ring chronologies collected from aspen, white spruce, and jack pine on natural sandy sites in the oil sands region, Seely and Welham (2008; unpublished) found a weak positive relationship with temperature but a stronger relationship with growing season precipitation (June – August cumulative rainfall). The latter was further improved when a threshold was applied to maximum growing season precipitation. These thresholds were species-specific. Using climate data from two sequential years produced the strongest relationships, with a maximum value for pine ($r^2 = 0.84$).

Barber et al. (2000) showed that over the previous 90 years, radial growth in Alaskan white spruce had decreased with increasing temperature. The data indicated that temperature-induced drought stress had disproportionately affected the most rapidly growing white spruce, suggesting that drought may be an important factor limiting productivity in the North American boreal forest.

Models have been developed to simulate tree ring growth in relation to climate variables. In the southeastern US, Anchukaitis et al. (2006), employed a deterministic model linking daily temperature, precipitation, and daylength to ring-width variations in conifers, and were able to successfully simulate regional patterns of climate-tree growth relationships.

1.4 Project Objectives

The overall objective of this project is to develop a framework that integrates risk management and strategic decision-making in order 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 will include an evaluation of the impact of disturbance (natural disturbance due to insect outbreaks, fire and wind, as well as other industrial and agricultural disturbances), conservation, and reclamation activities associated with oil sands development both at the lease and regional levels.

The project will be conducted in three phases. Each phase is sequential such that its results and conclusions represent the foundation for the subsequent work. In this way, project investment and outcomes can be realized incrementally. This has the benefit that (a) project funding can be tied to realized outcomes at specific intervals during project implementation, (b) deliverables will be available in a more timely fashion, and (c) interim results can be used to guide subsequent activities and refine project outcomes.

Four scenarios will be incorporated into the overall project. These include scenarios constituting a basecase analysis, climate change, mine development plans, and regional development plans. The basecase scenario is a series of outcomes derived with no consideration for future climate change. The importance of the basecase is that it represents the null condition and thus provides a context for comparing the relative impact of different climate change scenarios (the focus of subsequent project activities). The basecase scenario was the main focus of the work conducted in this Phase I report.

2 A DENDROCHRONOLOGY ANALYSIS OF THE RELATIONSHIP BETWEEN CLIMATE AND TREE GROWTH IN FOUR TREE SPECIES

2.1 Summary

The dendrochronology work 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 review of on-line and literature sources was used to identify tree core collections from the region. A total of 29 chronologies were identified that matched a set of suitability criteria: 18 chronologies for white spruce, 8 for jack pine, 2 for black spruce and 1 for trembling aspen. In addition, 9 aspen chronologies were analyzed from field cores collected in the Athabasca region. Each core series was used to date tree rings by year of growth and to create master chronologies of ring width over the previous 75 years (1935 to 2009). Residual chronologies were generated by standardizing and detrending master chronologies to remove non climate-related influences on growth. These residual chronologies were then correlated to one or more of 25 climate-related variables derived from climate records obtained from nearby weather stations. Preliminary results indicated that radial growth of white spruce was limited by current year water stress; significant relationships were found between radial growth and growing season precipitation and summer temperatures. Similar results were found for jack pine, but no conclusive results were found for trembling aspen or black spruce. Subsequent work will be required to (a) add additional data sources, particularly for aspen, and (b) to determine whether additional climate relationships may better explain ring chronologies.

2.2 Introduction

The overall objective of the dendrochronology work was to develop mathematical relationships between ring width and climate that could be used to predict future tree growth under changing climate conditions in Alberta's boreal forest, and as a source of calibration data for the ecosystem simulation model, FORECAST Climate.

Specific objectives for the dendrochronology work were:

1. Review the scientific literature on the influence of climate on tree growth.
2. Identify available dendrochronologies for the target species (white spruce, aspen, jack pine, and black spruce) and associated climate data.
3. Conduct initial tests of the relationship between radial growth chronologies and a selection of climate variables using correlations, regressions and other statistical techniques.
4. Generate equations to predict tree radial growth from climate variables (work will be completed by the end of Phase II).

2.3 Methods

2.3.1 *Bibliography Review on the Effects of Climate on Tree Growth*

A total of 210 scientific papers were reviewed on the effect of climate (as defined by the most common variables: air temperature and precipitation) on tree growth. The review was conducted on literature available from scientific journals, scientific books, scientific workshops and conference proceedings, and technical reports. Bibliographical databases used were:

- *Bibliography of Dendrochronology* (compiled by Dr. Grissino-Mayer, University of Arizona). Available at http://www.wsl.ch/dbdendro/index_EN?redir=1&
- *Bibliography of Canadian Tree ring Research* (compiled by Dr. Dan Smith, University of Victoria). Available at http://cgrg.geog.uvic.ca/cgi-bin/cdsearch.cgi
- *Canadian Forest Service Bookstore* (compiled by the Canadian Forest Service). Available at http://bookstore.cfs.nrcan.gc.ca/
- *ISI Web of knowledge* (academic search engine by Thomson Reuters). Available at http://www.isiwebofknowledge.com/
- *Google Scholar* (academic search engine by Google Inc.). Available at http://scholar.google.ca/

About one quarter of the papers were focused on studies at global scales, another quarter were related to simulation of climate effects in models, another quarter dealt with reviews, comments and theoretical relationships between climate and decomposition, and the remainder were focused on field studies carried out in North America.

2.3.2 *Tree Ring Chronologies*

Chronologies were obtained from the World Data Centre for Paleoclimatology, hosted by the US National Oceanic and Atmospheric Administration (NOAA; available online at: http://www.ncdc.noaa.gov/paleo/treering.html).

Additional chronologies were obtained from the Boreal Ecosystem-Atmosphere Study (BOREAS http://daac.ornl.gov/BOREAS/bhs/BOREAS_Home.html) (Sellers et al. 1997), and from the dendrochronological collections of Dr. Ted Hogg (Canadian Forest Service, Northern Forestry Centre, http://cfs.nrcan.gc.ca/directory/thogg) and Dr. Ellen McDonald (University of Alberta, Department of Renewable Resources).

Only chronologies that matched the following criteria were selected:

- Located in the mixedwood section of the boreal forest ecoregion, within the boreal plains ecozone.
- Any of four target species; white spruce (*Picea glauca*), black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), and trembling aspen (*Populus tremuloides*).
- Elevation lower than 1,000 m.a.s.l.
- Located in Alberta or Saskatchewan (latitude between 53° N and 58° N, and longitude between 122° W and 106° W).
- More than 50 years of tree ring records, with the last year of record 1989, or later.

A total of 38 chronologies were identified that matched all the criteria. There were 18 chronologies for white spruce, 8 for jack pine, 2 for black spruce and 10 for trembling aspen (Table 1).

2.3.3 *Climate Data*

Climate data were obtained from Canada's National Climate Archive (http://www.climate.weatheroffice.ec.gc.ca) housed by Environment Canada. Locations of weather stations and sampling sites for dendrochronological data are plotted in Figure 1. The reference stations for each chronology were selected based in proximity to a given dendrochronological sample. Most weather stations were located in the southern half of both provinces, and this set a limitation on the number of weather stations suitable for the analysis. Descriptive information for the selected weather stations is provided in Table 2. A statistical correlation analysis was conducted among the weather series data for monthly temperature and precipitation to determine their overall similarity in climate.

Table 1. Selected dendrochronologies for four tree species in the boreal forest of Alberta and Saskatchewan

ID	Species	Province	Altitude (m)	Latitude (° ‘)		Longitude (° ‘)		Climate station	Years		Reference
BOREAS 2	Aspen	SK	550	53	52	105	31	Choiceland	1909	1994	Sellers et al. (1997)
CAL	Aspen	AB	630	55	17	112	58	Calling Bay	1951	2000	Ted Hogg’s chronology
PET	Aspen	SK	470	56	44	108	45	Buffalo Narrows	1923	2000	Ted Hogg’s chronology
RED	Aspen	AB	510	56	53	115	17	Red Deer	1946	2000	Ted Hogg’s chronology
HIG	Aspen	AB	340	58	19	117	14	High Level	1942	2000	Ted Hogg’s chronology
TAT	Aspen	SK	660	54	37	109	37	Cold Lake	1944	2000	Ted Hogg’s chronology
CL	Aspen	AB	-	58	25	116	32	High Level	1950	2007	Purdy et al. (2005)
SL	Aspen	AB	-	57	5	111	31	Fort McMurray	1877	2005	Purdy et al. (2005)
SP	Aspen	AB	-	59	51	112	23	Fort Chipewyan	1945	2006	Purdy et al. (2005)
ZM	Aspen	AB	-	58	43	119	5	High Level	1936	2006	Purdy et al. (2005)
NOAA 207	Black spruce	SK	360	56	39	103	12	Whitesand Dam	1835	2001	Beriault and Sauchyn (2006)
BOREAS 3	Black spruce	SK	550	53	52	105	31	Choiceland	1867	1994	Sellers et al. (1997)
NOAA 132	Jack pine	AB	-	59	45	112	12	Fort Chipewyan	1849	1992	Larsen (1997)
NOAA 133	Jack pine	AB	300	59	35	111	20	Fort Chipewyan	1849	1992	Larsen (1997)
NOAA 196	Jack pine	SK	426	57	51	103	50	Collins Bay	1817	2002	Beriault and Sauchyn (2006)
NOAA 200	Jack pine	SK	510	57	33	106	53	Cree Lake	1766	2002	Beriault and Sauchyn (2006)
NOAA 201	Jack pine	SK	500	56	49	107	35	Cree Lake	1875	2002	Beriault and Sauchyn (2006)
NOAA 203	Jack pine	SK	540	57	4	105	30	Key Lake	1832	2002	Beriault and Sauchyn (2006)
NOAA 204	Jack pine	SK	500	57	25	106	8	Key Lake	1854	2002	Beriault and Sauchyn (2006)
NOAA 208	Jack pine	SK	410	56	30	102	58	Whitesand Dam	1878	2002	Beriault and Sauchyn (2006)
NOAA 129	White spruce	AB	-	59	59	112	21	Fort Chipewyan	1824	1989	Larsen (1997)
NOAA 130	White spruce	AB	-	59	48	112	10	Fort Chipewyan	1814	1989	Larsen (1997)
NOAA 131	White spruce	AB	-	59	7	112	11	Fort Chipewyan	1865	1989	Larsen (1997)
NOAA 145	White spruce	SK	590	55	7	105	9	Lac La Ronge	1971	1994	Beriault and Sauchyn (2006)
NOAA 197	White spruce	SK	425	57	52	103	48	Collins Bay	1852	2002	Beriault and Sauchyn (2006)
NOAA 198	White spruce	SK	315	54	56	102	47	Island Falls	1839	2001	Beriault and Sauchyn (2006)
NOAA 202	White spruce	SK	390	55	42	106	36	Lac La Ronge	1840	2001	Beriault and Sauchyn (2006)
NOAA 205	White spruce	SK	360	55	38	104	44	Lac La Ronge	1879	2002	Beriault and Sauchyn (2006)
NOAA 206	White spruce	SK	370	55	13	104	32	Lac La Ronge	1827	2001	Beriault and Sauchyn (2006)
NOAA 212	White spruce	SK	209	59	0	112	0	Fort Chipewyan	1698	2000	Meko (2006)
NOAA 213	White spruce	SK	209	58	48	111	30	Fort Chipewyan	1712	2000	Meko (2006)
NOAA 214	White spruce	SK	213	58	54	111	36	Fort Chipewyan	1801	2000	Meko (2006)
NOAA 215	White spruce	SK	213	58	54	111	24	Fort Chipewyan	1742	2000	Meko (2006)
NOAA 216	White spruce	SK	209	59	0	111	24	Fort Chipewyan	1687	2000	Meko (2006)
NOAA 217	White spruce	SK	220	58	24	111	30	Fort Chipewyan	1708	2000	Meko (2006)
NOAA 218	White spruce	SK	250	58	30	112	30	Fort Chipewyan	1757	2000	Meko (2006)
NOAA 219	White spruce	SK	250	58	36	111	18	Fort Chipewyan	1801	2000	Meko (2006)
BOREAS 1	White spruce	SK	550	53	52	105	31	Choiceland	1871	1994	Sellers et al. (1997)

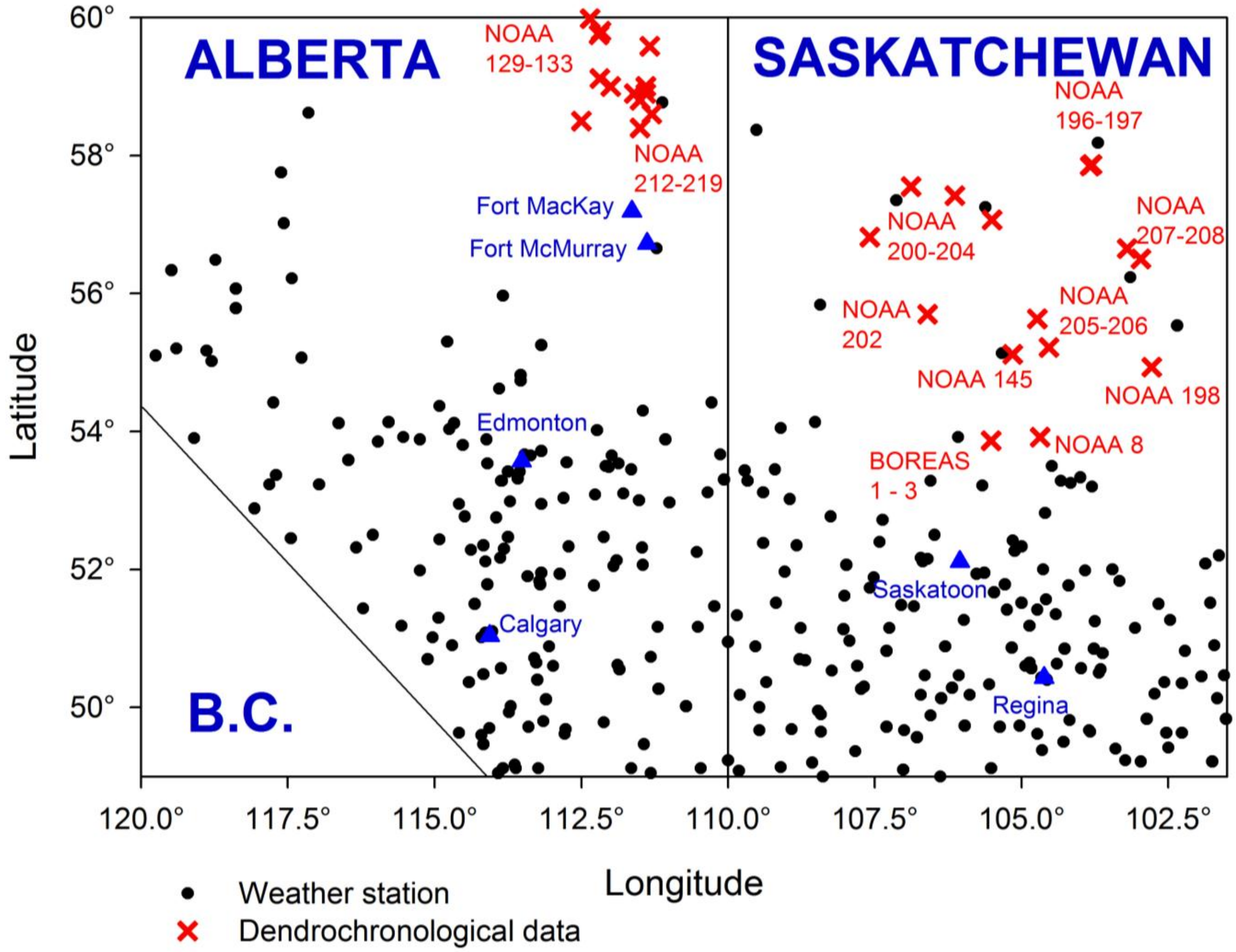


Figure 1. Network of weather stations in Alberta and Saskatchewan (black dots) and sites from where dendrochronological data were obtained

Red crosses indicate location, and red letters denote a given tree ring series.

Table 2. Average values from selected weather stations

Station	Province	Altitude	Latitude	Longitude	Average annual T		Average annual P	
		m.a.s.l.			°C	years	mm	years
Choiceland	SK	442.0	53° 30' N	104° 29' W	0.8	1948 - 1994	483.7	1948 - 1994
Cree Lake	SK	494.6	57° 21' N	107° 8' W	-2.3	1965 - 1993	445.7	1965 - 1993
Collins Bay	SK	491.9	58° 11' N	103° 42' W	-4.0	1972 - 2007	551.6	1972 - 2007

Station	Province	Altitude	Latitude	Longitude	Average annual T		Average annual P	
		m.a.s.l.			°C	years	mm	years
Fort Chipewyan	AB	232.0	58° 46’ N	111° 7’ W	-1.7	1967 - 2007	367.9	1967 - 2007
Island Falls	SK	299.3	55° 32’ N	102° 21’ W	-1.5	1929 - 2007	507.8	1929 - 2007
Key Lake	SK	509.0	57° 15’ N	105° 37’ W	-2.3	1976 - 2007	481.1	1976 - 2007
Lac La Ronge	SK	365.8	55° 8’ N	105° 20’ W	-0.9	1923 - 1942	526.7	1923 - 1987
Whitesand Dam	SK	344.0	56° 14’ N	103° 9’ W	-1.8	1938 - 2004	534.0	1938 - 2004
Calling Lake	AB	598.0	55° 15’ N	113° 11’ W	0.9	1971 - 2000	453.8	1971 - 2000
Red Deer	AB	846.7	52° 18’ N	113° 47’ W	3.4	1974 - 2000	487.2	1974 - 2000
High Level	AB	338.0	58° 37’ N	117° 9’ W	-1.3	1971 - 2000	394.1	1971 - 2000
Cold Lake	AB	541.0	54° 25’ N	110° 27’ W	1.7	1971 - 2000	426.6	1971 - 2000
Buffalo Narrows	SK	433.7	54° 49’ N	108° 26’ W	0.9	1979 - 2000	440.2	1979 - 2000

2.3.4 *Analysing the Tree Ring Chronologies*

The first step in creating a tree ring chronology is to verify the integrity of the core data. The software package COFECHA was used to assess the correlation in tree ring width between cores, the variability in a series of tree ring widths, and the correlation of tree ring width between current and previous years within a given core (Grissino-Mayer 2001). COFECHA also detects cores that are not significantly correlated with other cores from a given site, and cores that have outlier rings (ring widths are more than 3 standard deviations from the mean of all the ring widths for a particular year). COFECHA can thus be used to detect cores with potential issues in appropriate ring dating, detect possible missing rings, and to detect cores whose ring chronologies differ significantly from others within a site. The integrity of the core data had already been established in half of the total ring chronologies; hence, this step was performed on the remainder.

2.3.5 *Residual Chronologies*

Master chronologies were created by averaging the ring widths for all cores within a site for each year. However, master chronologies cannot be related directly to environmental variables because they reflect the natural trend in ring width that occurs independently of climate (overall ring widths are typically thicker in small trees and they get consistently thinner as the tree gets larger). To minimize this effect, chronologies must be detrended (removing the intrinsic variation) and standardized (dividing the actual ring width by the expected ring width for that year) (Fritts 2001), to create two new sequential chronologies: the standard chronology and the residual chronology. The standardization method is designed to remove the ring width variation unique to each individual tree and to simultaneously preserve all common variance resolvable from the age trend. In addition to removing the natural trend in ring width, standardization also scales the variance so that is approximately equivalent throughout the entire length of the time series. The resulting residual chronology then represents the deviations in ring width attributable to climate.

The standard and residual chronologies were created using the software package, ARSTAN (Cook 1985). It should be noted that the nature of the residual chronologies depends on which detrending function is used. We used the default double detrending function specified in ARSTAN, an initial detrending with the negative exponential function (or a linear function if the exponential cannot be fitted) and a second round of detrending if required (not necessary in most cases).

2.3.6 *Correlation between Residual Chronologies*

The similarity of residual series was analyzed by conducting multiple correlations among tree ring series from different sites for each tree species.

2.3.7 *Relationships with Climate Variables*

A total of 25 climate-related variables were used in the initial correlation and regression analysis with the residual tree ring chronologies. These are:

- Seasonal degree-days above 5°C and 10°C from May to September and June to August, respectively.
- The previous variables for the sum of previous and current years.
- Seasonal precipitation from May to September and from June to August.
- Seasonal precipitation for the period June to August using only data from years with seasonal precipitation below the threshold of 150, 185 and 220 mm.
- Seasonal precipitation for the period June to August of current and previous year using only data from two consecutive years with accumulated seasonal precipitation below the threshold of 350, 400 and 450 mm.
- Seasonal precipitation for the period May to September of current year using only data from years with seasonal precipitation below the threshold of 290, 350 and 390 mm.
- Seasonal precipitation for the period May to September of current and previous year using only data from two consecutive years with accumulated seasonal precipitation below the threshold of 520, 590 and 660 mm.

In the second step of the analysis, those climate variables that were significantly correlated ($p < 0.05$) with a residual chronology were included in a forward stepwise regression. The significance threshold value for a variable to enter into the model was $r^2 = 0.12$. To reduce problems of co-linearity among variables, only the variable from the same family with the highest correlation coefficient was included. For example, if both annual degree-days above 5°C and 10°C for the same period were significantly correlated to the residual tree ring index chronology, only the variable with the highest initial correlation was included in the stepwise analysis.

2.4 Results and Discussion

2.4.1 *Literature Review*

Of the 210 scientific papers and reports reviewed, a total of 25 reported direct relationships between climate variables and tree ring width (Tables 3 and 4). Black spruce was the species for which more research has been reported (Table 3), followed by white spruce, trembling aspen and jack pine (Table 4).

2.4.1.1 Black spruce

No references were found to black spruce in Alberta. Results from Saskatchewan and Manitoba, indicated that average high spring temperatures and high summer precipitation from the previous year had a positive effect on tree radial growth. Other results showed that temperatures of current and previous summers had a significant negative influence on tree growth (Table 3, Figure 2). Higher spring temperatures produce longer growing seasons, which allows trees to grow thicker rings (Dunn et al. 2007, Rocha et al. 2006), whereas summer precipitation reduces water stress at the time when temperatures are best for growth. Two references reported June temperatures as a negative influence on growth versus five describing it as positive (Figure 2). These discrepancies are likely due to latitudinal differences between sites. The negative influence of June temperatures occurs in the southern boreal forests (leading to longer, drier summers), whereas June temperature has a positive influence on more northerly forests where productivity is temperature-limited. Amiro et al. (2006) and Hoffer (2007) report fall temperatures as positive influences on radial growth, probably because of an extended growing season. In general, temperature influenced Black spruce growth in the current growing year whereas precipitation effects were manifested from the previous year (Figure 2). The latter may be because adequate precipitation facilitates the supply of carbohydrate reserves at the end of the growing season and which is then used to fuel early growth in the subsequent year.

Table 3. Reported relationships between tree productivity and climate variables for black spruce (*Picea mariana*).

Reference	Region	Elevation	Positive relations	Negative relations
BLACK SPRUCE				
Arain et al. (2002)	Saskatchewan	-	T_{spring}	T_{summer}
Amiro et al. (2006)	Saskatchewan		T_{annual}, T_{spring}, $T_{early\ fall}$	
Dunn et al. (2007)	Manitoba	-	T_{spring}	
Rocha et al. (2006)	Manitoba	-	Moisture index (MI)	
Goulden et al. (1998)	Manitoba	-		T_{summer}
Brooks et al. (1998)	Manitoba (S BOREAS)	-	$P_{august-1}$, P_{march}	T_{june-1}, $T_{september-1}$, $T_{February}$, T_{june}
Brooks et al. (1998)	Manitoba (N BOREAS)	-		T_{july}
Girardin and Tardiff (2005)	South Manitoba	400	P_{july-1}, $P_{august-1}$, $P_{september-1}$	T_{july-1}, $T_{august-1}$, $T_{september-1,}$ $P_{october}$
Hoffer (2007)	Manitoba	250	$P_{august-1}$, $P_{september-1}$, $T_{november-1}$	T_{july-1}, $T_{august-1}$, $T_{september-1}$, T_{june}, $T_{summer-1}$
Jozsa et al. (1984)	North Manitoba	-	T_{june}	
Dunn et al. (2007)	Manitoba (N BOREAS)	-	T_{spring}	T_{summer}

Altitude in m.a.s.l.

T stands for average temperature

P for accumulated precipitation;

suffix “-1” indicates data from previous year; and “-“ indicates data not provided.

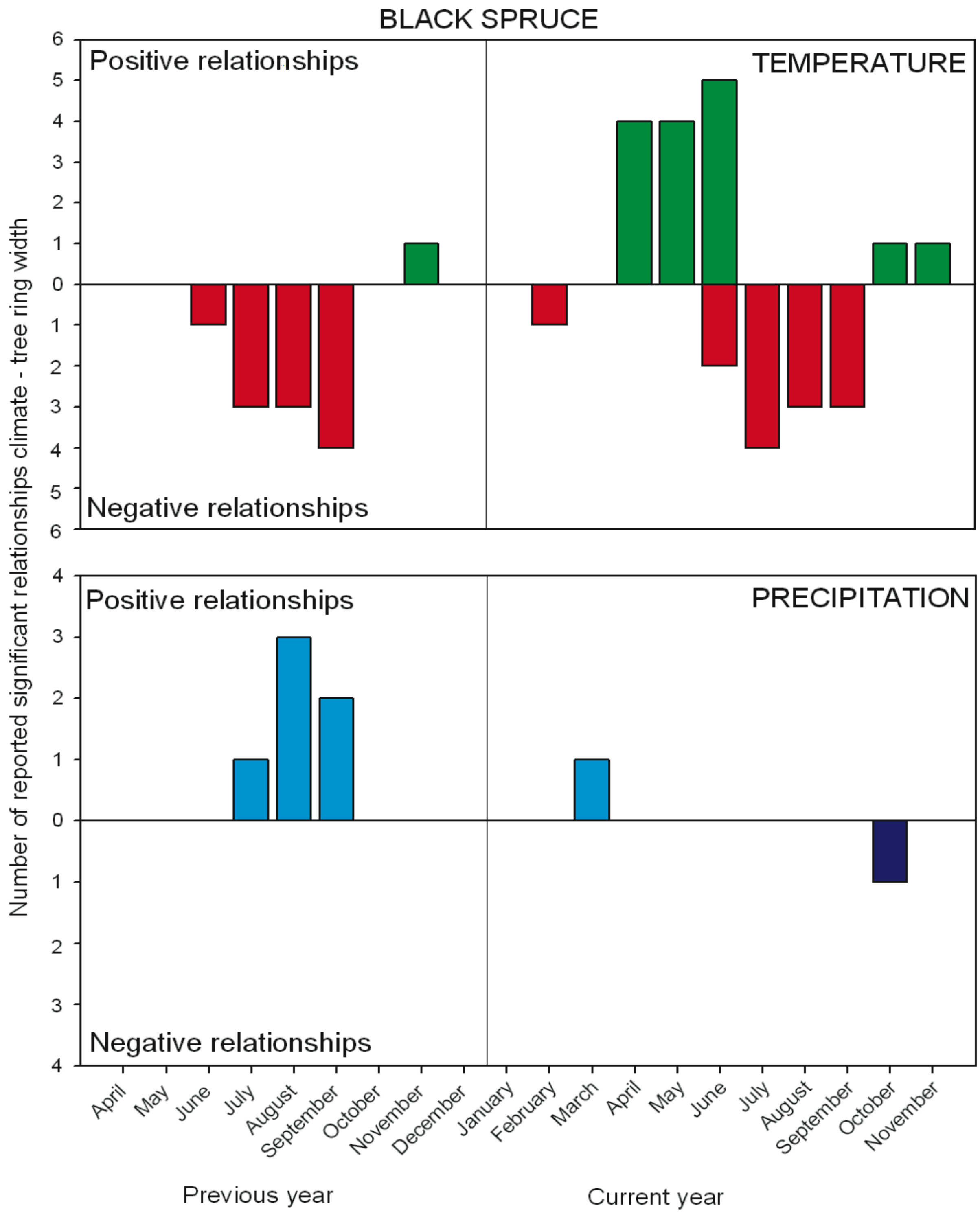


Figure 2. Number of bibliographic references to relationships between average monthly temperatures and tree ring width of black spruce in the boreal forest.

In conclusion, all reported results during this review support the hypothesis (Brooks et al. 1998) that black spruce is limited by hot and dry summer conditions along its whole range, with a biannual influence on growth: precipitation from the previous year and temperature in the current year.

2.4.1.2 White spruce

Most of the published work on white spruce was conducted in Manitoba, with a single reference from Alberta and northern BC (Table 4). Tree ring – climate relationships in white spruce were similar to those of black spruce, but with a benefit from precipitation during the current growing season (Table 4, Figure 3). Spring temperatures appear to have little effect on radial growth. On the other hand, high summer temperatures during both previous and current growing seasons were found to reduce tree radial growth (Figure 4). For those same periods, positive relationships between the amount of precipitation and tree ring width were also reported (Figure 4). It has been suggested that conditions at the end of the growing season have a strong influence on the carbohydrate reserves used to fuel growth in the subsequent growing season (Fritts 2001, Kozlowski and Pallardy 1997, Zahner 1968). This is reflected in a strong positive response in current-year ring width to previous August and September precipitation, and a negative correlation to previous September temperatures (Table 4, Figure 3). High September temperatures may increase evapotranspiration demands and may lead to an increased rate of respiration and thus deplete carbohydrate reserves for the following year (Kozlowski et al. 1997). Chhin et al. (2004) concluded that white spruce growth is sensitive to climatic fluctuations because growth is restricted by moisture deficiency; from the available scientific literature it appears that temperature is of secondary importance.

2.4.1.3 Jack pine

There is an overall lack of information available on tree ring – climate relationships for jack pine, and no reports from Alberta (Table 4). Jack pine appears to have a similar response to that of black spruce, with ring width positively related to summer precipitation and spring temperatures in the current year (Figure 4). Brooks et al. (1998) suggest that their results support the idea that moisture limits the southern range of jack pine and cold soil temperatures limit the northern extent.

Table 4. Reported relationships between tree productivity and climate variables for white spruce (*Picea glauca*), jack pine (*Pinus banksiana*) and aspen (*Populus tremuloides*).

Reference	Region	Elevation	Positive relations	Negative relations
WHITE SPRUCE				
Jozsa et al. (1984)	Central Alberta	-	T_{august}	
Chhin and Wang (2005)	S Manitoba	360	$P_{september-1}$, P_{may}, P_{june}, P_{july}, $MI_{august-1}$, $MI_{September-1}$, MI_{may}, MI_{june}, MI_{july}	$P_{february}$, $Tmin_{july-1}$, $Tmax_{june}$, $Tmax_{july}$, T_{july}
Chhin and Wang (2008)	S Manitoba	360	P_{june}	T_{june}
Chhin et al. (2004)	S Manitoba	360	$P_{august-1}$, $P_{september-1}$, P_{may}, P_{june}, P_{july}, $MI_{august-1}$, $MI_{September-1}$, MI_{may}, MI_{june}, MI_{july}, $T_{february}$	T_{july-1}, T_{june}, T_{july}, $Tmax_{september-1}$, $Tmax_{june}$, $Tmax_{july}$
Flower (2008)	Interior North BC	1100	$Tmin_{june}$, $Tmin_{july}$, $Tmax_{may}$, $Tmax_{june}$, $Tmax_{july}$, T_{june}, T_{july}	$Tmin_{april}$
Girardin and Tardiff (2005)	South Manitoba	400	P_{july-1}, T_{april}	T_{july-1}, $T_{august-1}$, $T_{september-1}$, T_{june}, T_{july}
Wang et al. (2006)	South Manitoba	-	$T_{december-1}$, $T_{february}$, P_{july-1}, P_{may}, P_{june}, P_{july}	$Tmax_{November-1}$, T_{may}, T_{june}, T_{july}
JACK PINE				
Girardin and Tardiff (2005)	South Manitoba	400	T_{april}, P_{july-1}, $P_{august-1}$, P_{july}, P_{august}	$T_{august-1}$, $T_{september-1}$
Brooks et al. (1998)	Manitoba (S BOREAS)	-	P_{may}, $T_{january}$	
Brooks et al. (1998)	Manitoba (N BOREAS)	-	P_{may}, T_{april}	$P_{december-1}$, P_{march}
Amiro et al. (2006)	Saskatchewan	-	T_{spring}	
TREMBLING ASPEN				
Girardin and Tardiff (2005)	South Manitoba	400	P_{june}	T_{july-1}, $T_{august-1}$, $T_{september-1}$, $T_{february}$, T_{march}
Barr et al. (2007)	Central Saskatchewan	601	P_{summer}, T_{spring}	
Hoffer (2007)	Manitoba	250	$T_{november-1}$, T_{april}, T_{spring}, P_{june}	$P_{december-1}$, P_{july}, P_{summer}
Boone et al. (2004)	S Manitoba	-	P_{may-1}, $P_{september-1}$	T_{june}, $P_{february}$
Brandt et al. (2003)	AL – SK – MN	-	P_{summer}	

Altitude in m.a.s.l.; T stands for average temperature; P for accumulated precipitation; suffix “-1” indicates data from previous year; and “-“ indicates data not provided.

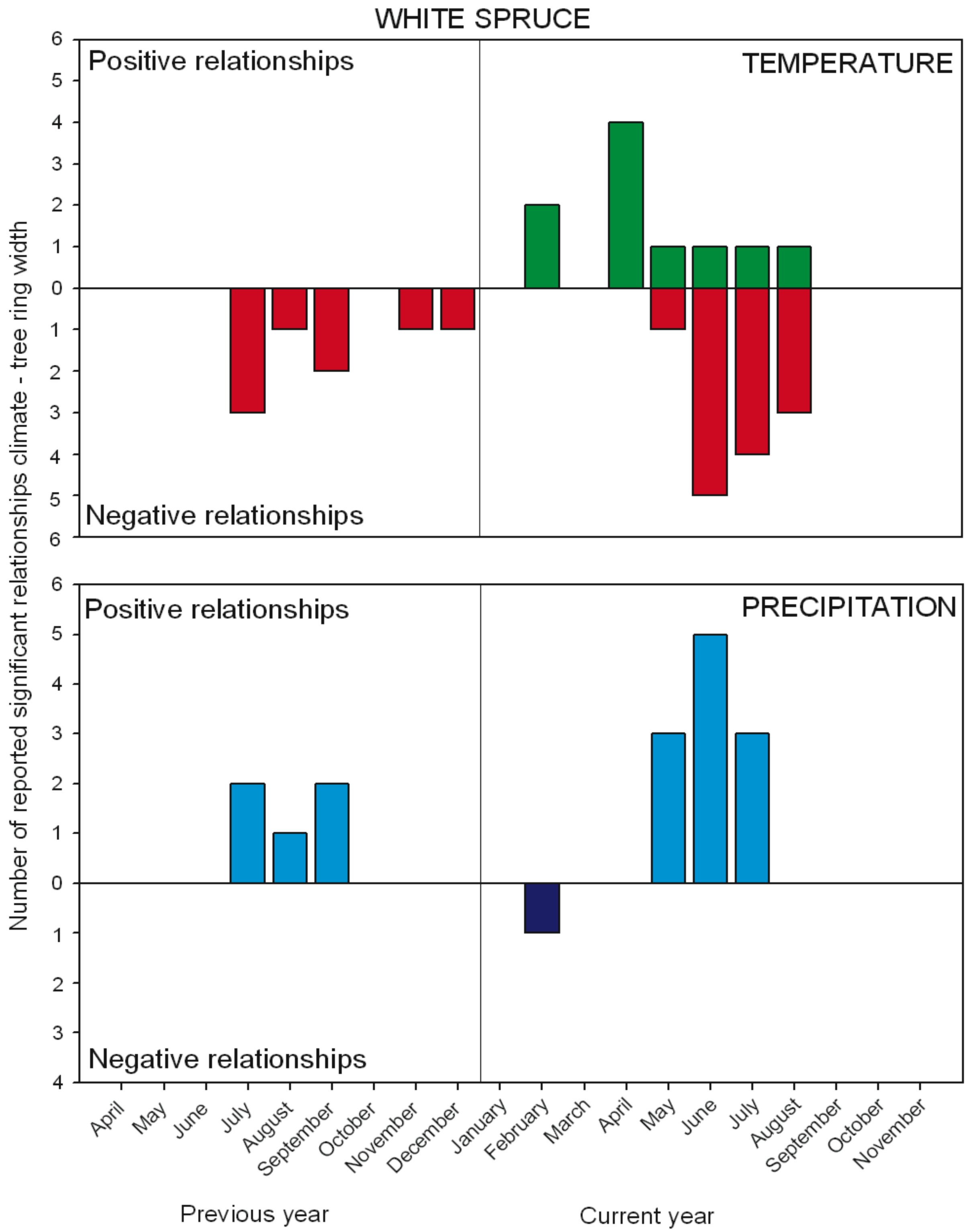


Figure 3. Number of bibliographical references to relationships between average monthly temperatures and tree ring width of white spruce in the boreal forest.

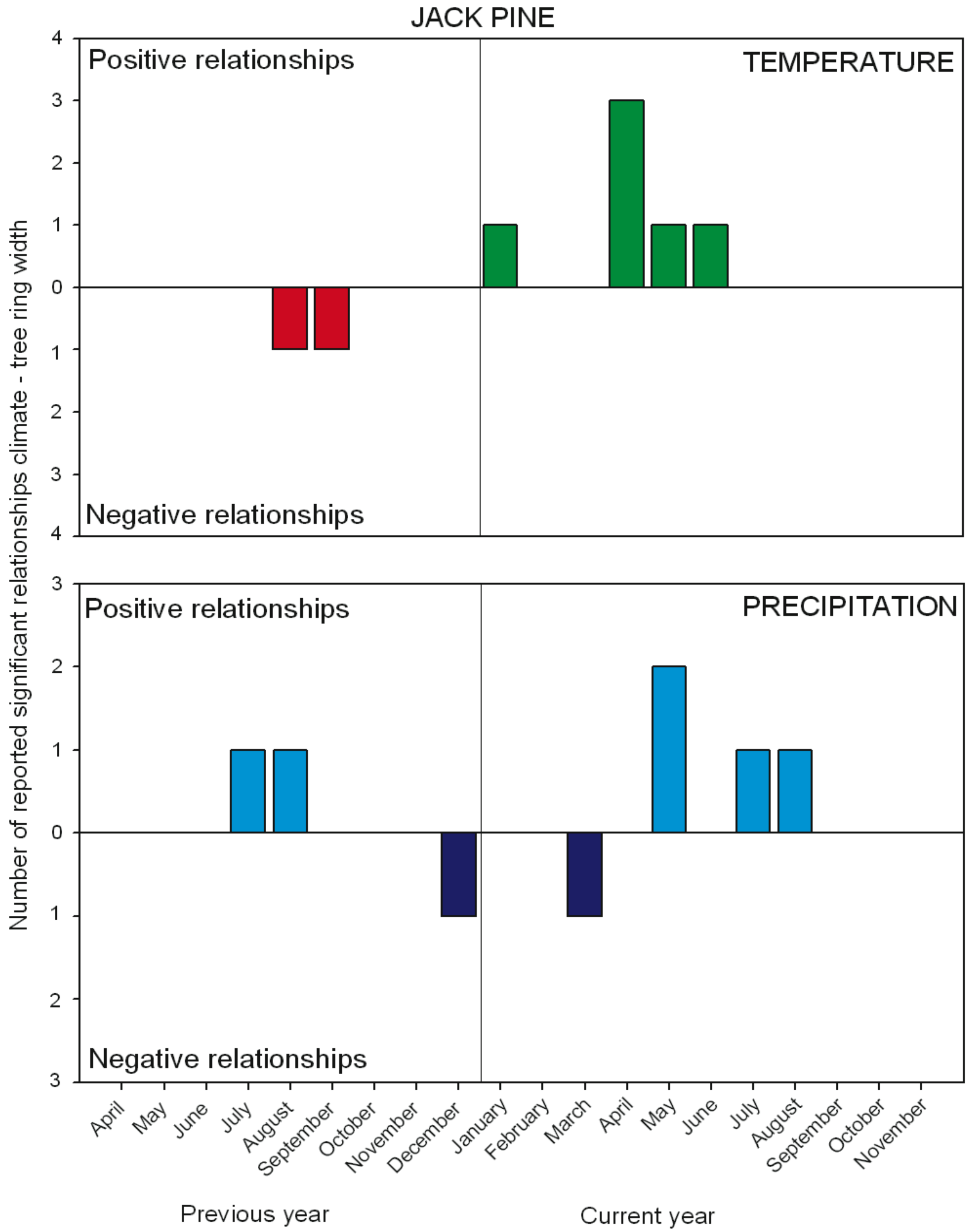


Figure 4. Number of bibliographical references to relationships between average monthly temperatures and tree ring width of jack pine in the boreal forest.

2.4.1.4 Trembling aspen

Tree growth – climate relationships for aspen are more inconsistent than for the other species. Most of the reported research has been conducted in Manitoba, Saskatchewan and NE British Columbia, with no reports for Alberta. From the literature it seems that high temperatures in spring of the current year can have a positive relationship with radial growth. However, a few references indicate that high temperatures in previous summer could be negatively related to ring width. As for precipitation, higher summer precipitation in the current year has been found to be related to wider rings, but a negative relationship has also been described (Table 4, Figure 5). Barr et al. (2007) noted that given the strong linkage between carbon uptake by boreal deciduous forests and spring temperature that has been observed in Saskatchewan (see also Baldocchi et al. 2001), it was surprising that the regional scale tree ring analysis of Hogg et al. (2005) found that aspen tree growth was more affected by interannual variation in moisture and insect defoliation than temperature. Leonelli et al. (2008) provided evidence that aspen sensitivity to climate varied along a productivity gradient. In general, high-productivity sites showed higher negative and positive correlations for the monthly temperature and precipitation variables of the previous year, respectively. The positive correlation with precipitation, along with the negative correlation with temperature during the summer of the year prior to growth, suggests that summer water balance limits the production of assimilates that are used for tree ring formation in the following year, particularly at high-productivity sites.

2.4.2 *Correlations among Weather Stations*

Weather patterns from stations in Alberta and Saskatchewan were highly positively correlated (Table 5), despite their geographic separation (Table 2). This may not be surprising. The low topographic relief characteristic of the region allows weather systems to move easily across the Prairie Provinces (Natural Resources Canada 2009). More importantly, this suggests that the temperature – ring width relationships reported for Saskatchewan and Manitoba, may be directly applicable to Alberta.

Monthly precipitation among weather stations was also positively correlated and generally high (Table 5). However, the strength of the correlation was reduced as the distance between the weather stations increased. For example, the weakest correlation ($r = 0.454$) was found between Fort Chipewyan (north Alberta) and Choice Land (central Saskatchewan). It should be noted that average annual precipitation is very similar across the boreal forest region, with all the weather stations in Saskatchewan reporting between 445 and 551 mm total precipitation $year^{-1}$. However, Fort Chipewyan, the only station in Alberta, reported the least precipitation (367 mm $year^{-1}$) (Table 2). This station is also the one with the lowest correlations for accumulated monthly precipitation, although they are all still reasonably high and statistically significant (Table 6). This suggests that extrapolation of relationships between precipitation-related variables and tree ring width to distant areas is possible but should be performed with caution.

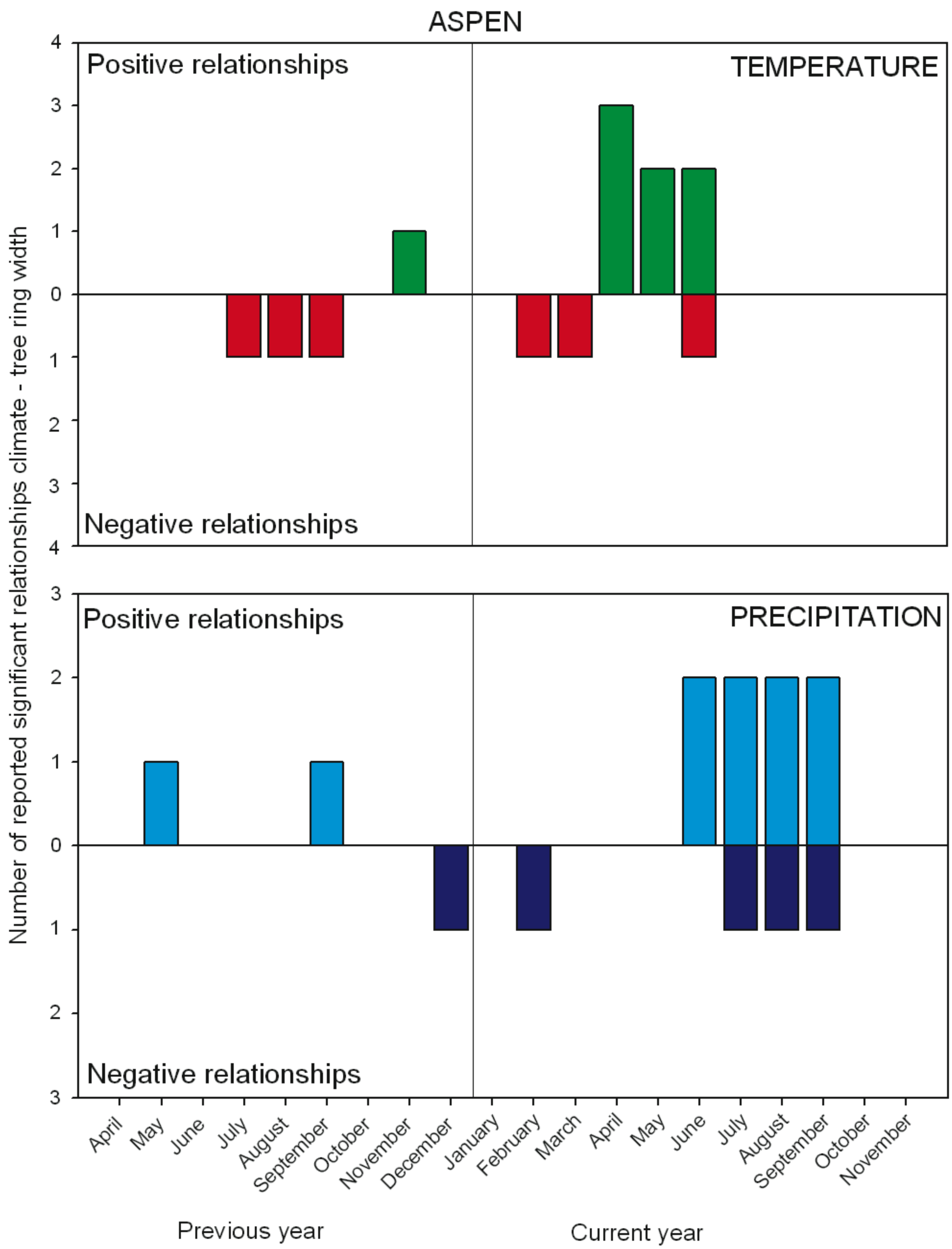


Figure 5. Number of bibliographical references to relationships between average monthly temperatures and tree ring width of aspen in the boreal forest.

Table 5. Correlations between different weather stations for average monthly temperature.

	Whitesand	Key Lake	Island Falls	Fort Chipewyan	Cree Lake	Choiceland	High Level	Fort McMurray	Red Deer	Calling Lake	Cold Lake	Buffalo Narrows
White sand	1.000											
Key Lake	0.995	1.000										
Island Falls	0.997	0.998	1.000									
Fort Chipewyan	0.993	0.998	0.995	1.000								
Cree Lake	0.996	0.999	0.997	0.998	1.000							
Choicelands	0.989	0.994	0.995	0.991	0.993	1.000						
High Level	0.985	0.990	0.987	0.994	0.991	0.987	1.000					
Fort McMurray	0.990	0.994	0.992	0.995	0.995	0.993	0.994	1.000				
Red Deer	0.971	0.977	0.977	0.976	0.979	0.981	0.976	0.982	1.000			
Calling Lake	0.983	0.984	0.984	0.986	0.987	0.987	0.987	0.992	0.988	1.000		
Cold Lake	0.986	0.990	0.990	0.990	0.992	0.993	0.989	0.996	0.989	0.995	1.000	
Buffalo Narrows	0.885	0.884	0.887	0.881	0.883	0.885	0.876	0.880	0.875	0.878	0.881	1.000

All correlations significant at $p < 0.05$. Series from Key Lake and Lac La Ronge were not included in the analysis due to an insufficient time span.

Table 6. Correlations between different weather stations for accumulated monthly precipitation.

	Whitesand	Key Lake	Island Falls	Fort Chipewyan	Cree Lake	Choiceland	High Level	Fort McMurray	Red Deer	Calling Lake	Cold Lake	Buffalo Narrows
White sand	1.000											
Key Lake	0.713	1.000										
Island Falls	0.712	0.632	1.000									
Fort Chipewyan	0.703	0.854	0.685	1.000								
Cree Lake	0.461	0.400	0.464	0.346	1.000							
Choicelands	0.829	0.645	0.666	0.715	0.523	1.000						
High Level	0.806	0.657	0.621	0.677	0.495	0.824	1.000					
Fort McMurray	0.605	0.577	0.596	0.700	0.479	0.656	0.636	1.000				
Red Deer	0.445	0.531	0.500	0.519	0.599	0.509	0.497	0.605	1.000			
Calling Lake	0.616	0.546	0.683	0.627	0.547	0.688	0.605	0.694	0.690	1.000		
Cold Lake	0.602	0.458	0.541	0.544	0.474	0.639	0.634	0.608	0.460	0.590	1.000	
Buffalo Narrows	0.641	0.536	0.666	0.590	0.589	0.769	0.721	0.665	0.660	0.788	0.726	1.000

All correlations significant at $p < 0.05$. Series from Collins Bay and Lac La Ronge were not included in the analysis due to an insufficient time span.

2.4.3 *Correlations among Tree Ring Chronologies*

Tree ring chronologies were remarkably similar among sampling areas and for all species. For black spruce, the only two chronologies available for analysis had a significant positive correlation (r = 0.319, p = 0.024). In the case of jack pine, chronologies were significantly correlated even when they were sampled from distant regions; the one exception is the NOAA 201 – NOAA 208 correlation (Table 7). Hence, annual variations in jack pine tree ring width have been consistent across the boreal forest region for at least the last century (Fritts 2001), and therefore climate – growth relationships from one area can be considered as valid proxies for relationships elsewhere.

Table 7. Correlations among different tree ring series for jack pine.

	NOAA 132	**NOAA 133**	**NOAA 196**	**NOAA 200**	**NOAA 201**	**NOAA 203**	**NOAA 204**	**NOAA 208**
NOAA 132	1.000							
NOAA 133	0.614	1.000						
NOAA 196	0.409	0.298	1.000					
NOAA 200	0.335	0.400	0.475	1.000				
NOAA 201	0.332	0.349	0.356	0.446	1.000			
NOAA 203	0.295	0.340	0.472	0.526	0.237	1.000		
NOAA 204	0.251	0.351	0.417	0.595	0.422	0.395	1.000	
NOAA 208	0.257	0.226	0.412	0.216	0.068*	0.353	0.239	1.000

All correlations positive and significant ($p < 0.05$) unless marked by an asterisk.

Results for aspen (Table 8) show generally weak relationships among chronologies. On saline sites, salinity can be as effective at inducing water stress as climate (Purdy et al. 2005).

Table 8. Correlations among different tree ring series for aspen.

	BOREAS 2	**PET**	**RED**	**CAL**	**TAT**	**HIG**	**SL**	**CL**	**ZM**	**SP**
BOREAS 2	1.000									
PET	-0.210*	1.000								
RED	0.021*	0.413	1.000							
CAL	-0.155*	0.295	0.074*	1.000						
TAT	-0.127*	0.355	0.114*	0.382	1.000					
HIG	-0.082*	0.108*	0.078*	-0.382	0.050*	1.000				
SL	0.018*	-0.001	0.164	0.226	-0.092*	0.098	1.000			
CL	0.274*	-0.001*	0.248*	-0.022*	-0.114*	-0.129*	-0.141*	1.000		
ZM	0.113*	0.123*	0.325	-0.277*	0.188*	0.535	-0.003*	-0.040*	1.000	
SP	-0.039*	0.085*	0.045*	-0.032*	0.020*	0.202*	0.275*	-0.205*	0.331*	1.000

All correlations positive and significant ($p < 0.05$) unless marked by an asterisk.

Correlations for white spruce show the same general consistency as for jack pine (Table 9). Of the 153 possible paired correlations, 89.5% were significantly positive with only 16 (10.5%) not significant. The NOAA 131 and NOAA 213 series were the two chronologies responsible for most of the non-significant correlations. The lack of significant correlations between those series and the remainder seems to be related to their northerly locations. Hence, there may be climatic features for these sites that are unique relative to the other sample locations. As with jack pine, the high number of positive correlations among the sampling sites in Alberta and Saskatchewan support the idea that the inter-annual variation in tree ring width has been similar for white spruce across this area of the boreal forest. Jozsa et al. (1984) also described high correlations between white spruce series sampled from sites in Alberta and Manitoba.

2.4.4 *Relationships between Residual Chronologies and Climate Variables*

Our analysis showed clear patterns in the influence of particular climate variables on radial growth (see Tables 10 and 11; see Appendix 1 for additional statistical data). For black spruce, jack pine and trembling aspen, no relationship with growing season degree-days was found, and for white spruce the relationship with degree-days was significant only in series NOAA 198 (Table 11). This strongly suggests that the single seasonal climate variable best related to radial growth in the boreal forest is precipitation. There were important differences between species: many more significant relationships were found for white spruce than for jack pine. Only one series of black spruce tree rings and none of trembling aspen were found to have significant relationships with climate variables. Sample size were simply too small for these species, however, to consider the conclusions as definitive.

The significant climate relationships for white spruce can be divided in two groups: the more northerly Alberta sites with most of the significant results related to the accumulated precipitation during the current growing season (Figure 6)(though other precipitation-related variables were also significant; Table A1-3), and the Saskatchewan sites where significant relationships were related mostly to the accumulated precipitation from previous and current growing seasons (Table 10). Although a range of precipitation thresholds were evaluated (Lo 2009), no clear improvements were observed when compared to the total accumulated growing season precipitation. This provides further support for the idea that water stress during the entire growing season and not only the summer months, is the most important limiting factor for spruce growth. Other studies have reported that spruce is sensitive to soil moisture conditions, and more so than to air temperature (Lo 2009, Savva et al. 2006, Zhang et al. 1999). It also appears that in Alberta, where precipitation is lower compared to the Saskatchewan sites (Table 2), summer water stress has a more important influence on tree radial growth. On sites with higher precipitation, trees can accumulate sufficient carbohydrate reserves at the end of each growing season to fuel growth in the next year. Hence, reduced water limitation allows trees to generate more biomass within a year and also to allocate more carbohydrate to reserves (Litton et al. 2007).

Table 9. Correlations among different tree ring series for white spruce.

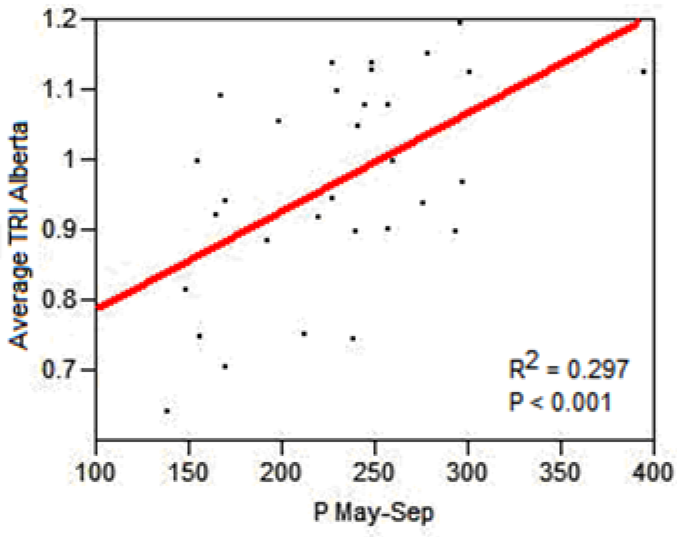
	NOAA 129	NOAA 130	NOAA 131	NOAA 145	NOAA 197	NOAA 198	NOAA 202	NOAA 205	NOAA 206	NOAA 212	NOAA 213	NOAA 214	NOAA 215	NOAA 216	NOAA 217	NOAA 218	NOAA 219	BOREAS 1
NOAA 129	1.000																	
NOAA 130	0.644	1.000																
NOAA 131	0.483	0.534	1.000															
NOAA 145	0.158	0.246	0.223	1.000														
NOAA 197	0.188	0.227	0.182*	0.114*	1.000													
NOAA 198	0.186	0.205	0.146*	0.519	0.303	1.000												
NOAA 202	0.230	0.252	0.131*	0.523	0.406	0.435	1.000											
NOAA 205	0.058*	0.145*	0.127*	0.560	0.244	0.637	0.466	1.000										
NOAA 206	0.244	0.352	0.301	0.608	0.349	0.483	0.585	0.549	1.000									
NOAA 212	0.608	0.547	0.639	0.274	0.303	0.317	0.326	0.131	0.308	1.000								
NOAA 213	0.531	0.502	0.534	0.199*	0.325	0.233*	0.365	0.098*	0.284	0.797	1.000							
NOAA 214	0.564	0.530	0.563	0.264	0.332	0.341	0.321	0.197	0.392	0.789	0.827	1.000						
NOAA 215	0.459	0.526	0.470	0.189*	0.274	0.295	0.374	0.167	0.279	0.708	0.796	0.777	1.000					
NOAA 216	0.547	0.519	0.611	0.255	0.331	0.332	0.279	0.161	0.313	0.881	0.796	0.856	0.738	1.000				
NOAA 217	0.417	0.406	0.431	0.289	0.282	0.310	0.444	0.196	0.347	0.635	0.720	0.655	0.667	0.623	1.000			
NOAA 218	0.411	0.384	0.428	0.230	0.241	0.318	0.314	0.265	0.292	0.637	0.668	0.600	0.642	0.584	0.620	1.000		
NOAA 219	0.350	0.389	0.366	-0.031*	0.292	0.163	0.172	0.012*	0.119	0.563	0.639	0.525	0.634	0.555	0.504	0.479	1.000	
BOREAS 1	0.122*	0.210	0.187	0.845	0.150*	0.455	0.441	0.472	0.498	0.241	0.185*	0.267	0.219	0.232	0.271	0.263	0.015*	1.000

All correlations significant ($p < 0.05$) unless marked by an asterisk.

Table 10. Significant correlations among residual tree ring chronologies and accumulated precipitation for different periods under different thresholds for white spruce.

Weather station / Tree ring series	**Accumulated P June-August current year** mm				**Accumulated P May-September current year** mm				**Accumulated P June-August previous and current years** mm				**Accumulated P May-September previous and current years** mm			
	Total	<180	<220	<250	Total	<290	<330	<350	Total	<350	<400	<450	Total	<520	<590	<660
Fort Chipewyan (AB)																
NOAA 129		✓														
NOAA 130	✓	✓		✓	✓		✓	✓								
NOAA 131			✓		✓	✓	✓	✓							✓✓	✓✓
NOAA 212	✓		✓	✓	✓✓	✓	✓✓	✓✓	✓		✓	✓	✓		✓	✓
NOAA 213	✓		✓	✓	✓✓	✓✓	✓✓	✓✓								
NOAA 214	✓		✓	✓	✓✓✓	✓	✓✓	✓✓					✓			
NOAA 215	✓			✓	✓		✓	✓								
NOAA 216					✓	✓	✓✓	✓✓							✓	
NOAA 217					✓✓		✓	✓								
NOAA 218					✓	✓	✓	✓								
NOAA 219	✓			✓	✓✓	✓	✓	✓					✓			
Lac La Ronge (SK)																
NOAA 145		✓														
NOAA 202									✓				✓✓			✓
NOAA 205							✓	✓	✓✓✓				✓✓		✓	
NOAA 206		✓							✓✓				✓✓✓			✓✓
Collins Bay (SK)																
NOAA 197									✓✓				✓			
Island Falls (SK)																
NOAA 198									✓							✓
Choiceland (SK)																
Boreas 1																

Significance levels are denoted as ✓: $P < 0.05$, ✓✓: $P < 0.01$, ✓✓✓: $P < 0.001$. All correlations are positive.



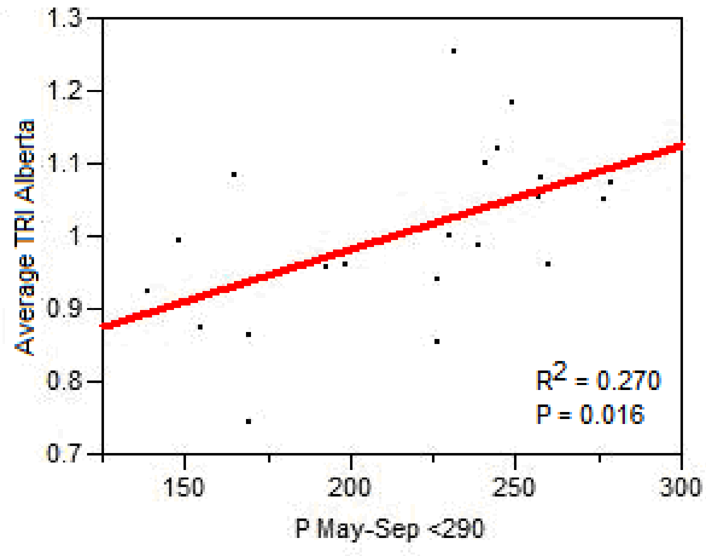
Tree Ring Index = 0.65019 + 0.0041 $P_{May\text{-}Sep}$

Figure 6. Linear regression between the average tree ring index (TRI) for Alberta's white spruce dendrochronological series and accumulated precipitation from May to September of current year.

The linear regression between the average tree ring index for Alberta white spruce and growing season accumulated precipitation was highly significant (Figure 6), and explained about 30% of the interannual variability in tree ring widths. This value for the regression coefficient is typical for dendroclimatological studies (Yu et al. 2007), and is in the same range as previous work (Briffa et al. 1990, Girardin et al. 2008, Graumlich 1991, Li et al. 2000, Lo 2009, Macías et al. 2006). Much of the unexplained variation is a reflection of variation in soil conditions and microclimatic which are not accounted for in the climate data (Fritts 2001).

In the case of jack pine, of the eight dendrochronological series, three had significant relationships with climate variables (Table 11). The only correlation in Alberta sites was found in the series NOAA 133, with highly positive correlation with accumulated precipitation from May to September for years with precipitation lower than 290 mm. In Saskatchewan, only one of six series was found to have significant correlations with summer precipitation (for years with less than 180 mm precipitation). These results indicate that summer water stress is not generally an important determinant of jack pine radial growth except during exceptionally dry years, and reflects the fact that this species is well adapted to the coarse textured, well-drained soils in which it is typically found. Extreme moisture deficits may be more of an issue in northeastern Alberta than in northern Saskatchewan given their differences in average annual precipitation (Table 2), though site-specific factors can also be important (Green and Miyamoto 2007, Pichler and Oberhuber 2007, Savva et al. 2006, Su et al. 2007, Zhang and Hebda 2004).

As with white spruce, a composite dendrochronology series for Alberta sites was created as the average of the available data. Correlations with climate variables indicated that the only variable significantly related to ring width was accumulated precipitation in the current growing season, but only for years with precipitation lower than a 290 mm threshold (Table A1-3). The associated regression showed a highly significant linear relationship, explaining 27% of the observed variability in ring width (Figure 7).



$$\text{Tree Ring Index} = 0.70293 + 0.00141\ P_{\text{May-Sep} <290}$$

Figure 7. Linear regression between the average tree ring index (TRI) for Alberta's jack pine dendrochronological series and accumulated precipitation from May to September of current year, for years of less than 290 mm.

Conclusions for black spruce were constrained by the low sample size. Of the two dendrochronological series, only one was found to have significant correlations with precipitation-related variables (Table 11). The strongest signal was accumulated precipitation of current growing season for years with less than 330 mm in the BOREAS 3 series. Secondary significant relationships were found with accumulated precipitation in previous and current growing seasons under a range of thresholds. These results indicate, at least in the BOREAS 3 series, that black spruce is sensitive to water stress but that higher amounts of water do not induce further radial growth. Previous studies have also reported water stress during the growing season as a limiting factor for black spruce growth during dry years (Case and Peterson 2005, Zhang et al. 2000).

Results for aspen were less clear (Table 12). Only two chronologies (HIG and CAL) showed more than one significant relationship with climate. In the case of HIG, accumulated summer precipitation in dry years was able to explain 48% of the variability of tree ring width (Figure 8). This coefficient value is much higher than is typical for this species (cf. Lo et al. 2010).

Table 11. Significant correlations among residual tree ring chronologies and accumulated precipitation for different periods under different thresholds for jack pine and black spruce.

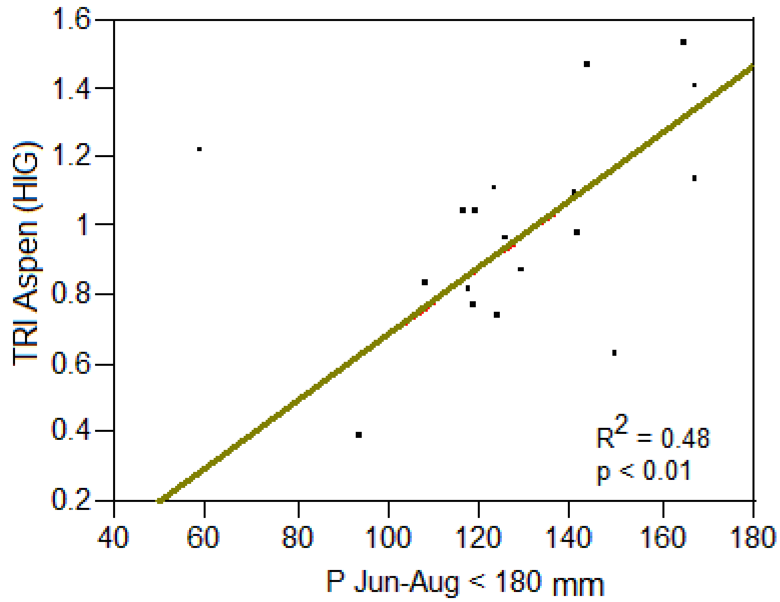
Weather station / Tree ring series	**Accumulated P June-August current year** mm				**Accumulated P May-September current year** mm				**Accumulated P June-August previous and current years** mm				**Accumulated P May-September previous and current years** mm			
	Total	<180	<220	<250	Total	<290	<330	<350	Total	<350	<400	<450	Total	<520	<590	<660
JACK PINE																
Fort Chipewyan (AB)																
NOAA 132																
NOAA 133						✓✓										
Collins Bay (SK)																
NOAA 196																
Cree Lake (SK)																
NOAA 200																
NOAA 201						✓										
Key Lake (SK)																
NOAA 204																
NOAA 203		✓														
Whitesand Dam (SK)																
NOAA 208																
BLACK SPRUCE																
Whitesand Dam (SK)																
NOAA 207																
Choiceland (SK)																
Boreas 3		✓	✓✓	✓		✓	✓✓✓	✓			✓✓	✓			✓	✓✓

Significance levels are denoted as ✓: $P < 0.05$, ✓✓: $P < 0.01$, ✓✓✓: $P < 0.001$. All correlations positive.

Table 12. Significant correlations among residual tree ring chronologies and accumulated precipitation for different periods under different thresholds for aspen.

Weather station / Tree ring series	**Accumulated P June-August current year** mm				**Accumulated P May-September current year** mm				**Accumulated P June-August previous and current years** mm				**Accumulated P May-September previous and current years** mm			
	Total	<180	<220	<250	Total	<290	<330	<350	Total	<350	<400	<450	Total	<520	<590	<660
Calling Lake (AB)																
CAL									✓				✓✓			
Red Deer (AB)																
RED		**(-)** ✓														
High Level (AB)																
HIGH		✓✓									✓	✓				
CL																
ZM																
Cold Lake (AB)																
TAT																
Fort McMurray (AB)																
SL																
Fort Chipewyan (AB)																
SP																
Buffalo Narrows (SK)																
PET							✓									
Choiceland (SK)																
BOREAS2																

Significance levels are denoted as ✓: $P < 0.05$, ✓✓: $P < 0.01$, ✓✓✓: $P < 0.001$. Negative correlations are indicated with the corresponding symbol.



$$\text{Tree Ring Index} = -0.289798 + 0.0097513 \,(\text{total P Jun-Aug})_{\text{threshold} < 180\text{ mm}}$$

Figure 8. Linear regression between the average tree ring index (TRI) for the aspen chronology in the HIG site and the accumulated precipitation from June to August, for years with less than 180 mm.

The low number of significant correlations in aspen may be due in part to the fact that four chronologies were obtained from naturally saline landscapes (Purdy et al. 2005). In these cases, water stress may be more related to direct salinity effects rather than a climate-mediated lack of soil moisture. As Purdy et al. (2005) point out, however, in the shrub and forest vegetation zones, surface soil salinity was similar between saline and non-saline landscapes, resulting in similar plant communities.

2.5 Final Thoughts

The accumulated literature evidence and analysis results indicate significant relationships between tree ring width and climate variables for white spruce and jack pine in the Alberta boreal forest. With a larger data series, similar relationships will likely also be obtained for black spruce and trembling aspen.

Radial growth for the four species in the Alberta boreal forest is linked primarily to water stress, which can be related to two basic climate variables: monthly average temperatures and monthly precipitation in summer months of the current year. In addition, white spruce radial growth is highly correlated with accumulated precipitation for the current growing season (from May to September), while jack pine radial growth is correlated to accumulated precipitation for the growing season but only during dry years (less than 290 mm for the total period). These results indicate that a relatively simple set of climate variables are sufficient to forecast the influence of future changing climate on tree radial growth. The level of variability explained by a single variable was around 30%, which is highly significant for these types of analyses (Hughes 2002). Nevertheless, climate alone cannot explain the majority of interannual variability in tree ring widths. Additional sources of variation such as competitive influences, community structure, soil properties, and nutrient variability also play an important role (Fritts 2001, Lo 2009). Hence, these factors must be included in any computer simulation tools used to project forest growth and productivity, in addition to climate (Kimmins 2008, Kimmins et al. 2008). One example of this approach is the FORECAST Climate model, an ecosystem-based, stand-level, forest management tool. FORECAST Climate simulates light interception, moisture dynamics, and nutrient cycling as key drivers of productivity in conjunction with an explicit representation of temperature and moisture regulation of photosynthesis, and competition for moisture between trees and minor vegetation. The model can simulate productivity and competition in overstory and understory tree populations, as well as minor vegetation (herbs, shrubs and bryophytes). FORECAST Climate will be applied as part of the Phase II work.

3 AN ASPATIAL ANALYSIS OF HABITAT SUITABILITY FOR 10 WILDLIFE SPECIES IN RELATION TO RECLAMATION ACTIVITIES

3.1 Summary

Much of the modeling work conducted within the oil sands has been focused around simulating vegetation productivity with little emphasis on the impact of community dynamics on development of wildlife habitat attributes. Hence, in this component of the Phase I work, habitat suitability indices were calculated using equations 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. Input values for each index were derived from output generated from the ecosystem simulation model, FORECAST. The development of each index was calculated from the initiation of reclamation through to mine closure as per practices described in the Kearl Lake Environmental impact Assessment (EIA) documents (Imperial Oil 2005).

Project objectives were as follows:

- Review of habitat suitability models that may be applicable to Alberta boreal forests.
- Identify variables used in the habitat suitability models that can be simulated with the FORECAST model.
- Simulate the reclamation prescriptions described in the Kearl Lake EIA documents with FORECAST and generate output suitable for populating each habitat suitability model.

- Generate habitat suitability indices (HSIs) for 10 wildlife species (identified from the review) on the Kearl Lake mine site and compare and contrast the temporal development of habitat from reclamation initiation to mine closure.

Conclusions were:

- There is a 37-year window following mine operation when upland habitat suitability is very poor on the mine footprint (an area that encompasses almost 30,000 ha).
- Habitat suitability recovers relatively quickly thereafter; 50 years after mine operation, 4 out of 10 species have a 100 % suitability index, and this increases to 9 out of 10 species 55 years after mine operation.
- The overall quality and pattern of recovery in habitat suitability depends on how much upland is reclaimed relative to the original (pre-mining) landscape.
- Deviations in the post-mining distribution of ecosite phases relative to the pre-mining landscape could have significant implications for the habitat suitability of particular species, either positively (more habitat is created) or negatively.
- The broad variation among species in their HSI values suggests that reclamation practices could be targeted towards the habitat requirements of one particular wildlife species by preferentially reclaiming more favourable ecosite phases. Conversely, a broad range of ecosite phases is necessary to promote suitable habitats for a diverse range of species on the reclaimed landscape.
- When habitat recovery rates on reclaimed sites are considered in conjunction with the overall mine footprint, it suggests that the impact of the operation is not trivial with respect to habitat loss.

3.2 Introduction

Over the next 10 years, oil sands production in the boreal mixedwood region of Alberta is expected to more than double. As a consequence, the projected disturbance footprint from all mining activities combined may be in the hundreds of thousands of hectares. Eventually, the entire disturbed area must be reclaimed to a capability equivalent to that which existed prior to the onset of mining. Hence, the goal of reclamation is to achieve self-sustaining ecosystems with ecological capabilities equivalent to the pre-disturbance conditions but which require no ongoing human maintenance.

Large piles of upland overburden and tailings sand are generated from the mining process. These materials have a low water storage capacity, nutrient status and organic carbon content. They are therefore capped with a mixture of organic peat and mineral soil (typically 50% each by volume) or other suitable soil materials. This mix constitutes the rooting matrix for the reclaimed plant community and is assumed to provide conditions sufficient to support the growth and development of a boreal mixedwood forest. Considerable empirical information is being acquired on the biogeochemistry of capping materials and its potential as a medium for plant growth. This empirical work is necessary to verify that ecosystem patterns and processes are consistent with anticipated outcomes. Unfortunately, empirical studies alone are not sufficient to guide reclamation planning and there is recognition that reclamation needs to be guided by model-based projections of future performance in conjunction with empirical data. Empirical information is limited by that fact that (a) Too much time is required before results can be considered as definitive. This lag period means that many years will have elapsed before ineffective practices and faulty assumptions are identified and corrected; (b) The total permutations and combinations of potential reclamation prescriptions is so vast that only a small subset is practical to study; and (c) Empirical studies are, by their very nature, a reflection of historical events and conditions. If future conditions differ significantly then past performance may be a poor predictor of future success. In this regard, climate simulations and weather records indicate that the climate in the Athabasca region is changing and this trend will increase throughout the century (Barrow and Yu 2005). Climate is a major driver of ecosystem development (Cayan et al. 2001, Flannigan et al. 1998, Li et al. 2000, Watson et al. 1996) and climate change casts doubt as to whether current reclamation practices are appropriate to future conditions. Several studies have shown that climate change is already affecting vegetation growth (e.g., Brubaker 1986, Graumlich 1991, Graumlich et al. 1989, Innes 1991, Peterson and Peterson 2001).

To date, much of the modeling work conducted within the oil sands has been focused around simulating vegetation productivity (though not within the context of climate change) with very little emphasis on the impact of community dynamics on development of wildlife habitat attributes. For models to be useful as tools for assessing the efficacy of different reclamation plans in achieving target objectives for wildlife, they need to be capable of representing stand features that determine the suitability of different habitats for terrestrial wildlife. A variety of tools have been developed to assist biodiversity planning in forest management, and among these are statistical models that quantify the relationship between the presence of a species and its habitat requirements. These models have gained popularity because habitat descriptors can be derived from variables commonly available in forestry databases or through modeling (e.g., timber volume, forest age, dominant tree height, and species composition)(Edenius and Mikusinski 2006). In North America's boreal forests, for example, models of habitat suitability have been developed for beaver (Allen 1983a), moose (Eccles et al. 1986), snowshoe hare, and black bear (Jalkotzy et al. 1990). When properly applied, these models can also predict the response of selected species to reclamation and evaluate the efficacy of alternative reclamation practices (Kliskey et al. 1999).

In this component of the Phase I work, habitat suitability indices were calculated for ten boreal forest wildlife species in natural forests and within reclamation plans developed as part of the Kearl Lake mine. Input values for each index were derived from output generated from the ecosystem simulation model FORECAST. The development of each index was calculated from the initiation of reclamation through to mine closure using practices as described in the Kearl Lake Environmental Impact Assessment (EIA) documents. Component objectives were:

1. Review of the habitat suitability models that may be applicable to Alberta boreal forests.

2. Identify variables used in the habitat suitability models that can be simulated with the FORECAST model.
3. Simulate the reclamation prescriptions described in the Kearl Lake EIA documents with FORECAST and generate output suitable for populating each habitat suitability model.
4. Generate habitat suitability indices (HSIs) for 10 wildlife species (identified from the review) on the Kearl Lake mine site and compare and contrast the temporal development of habitat from reclamation initiation to mine closure.

3.3 Methods

3.3.1 *Bibliographic Review of Wildlife Habitat Suitability Models*

A total of 50 scientific papers were reviewed on relationships between stand attributes and habitat suitability models for wildlife. The review was carried out with papers available in scientific journals, scientific books, proceedings of scientific workshops and conferences and technical reports. The bibliographical data bases used were:

- Canadian Forest Service Bookstore (compiled by the Canadian Forest Service). Available at http://bookstore.cfs.nrcan.gc.ca
- ISI Web of knowledge (academic search engine by Thomson Reuters). Available at http://www.isiwebofknowledge.com
- Google Scholar (academic search engine by Google Inc.). Available at http://scholar.google.ca
- CEMA Research library (collection of reports and publication for the Alberta oil sands area compiled by the Cumulative Environmental Management Association). Available at http://www.cemaonline.ca
- UBC. library (academic library at the University of British Columbia). On-line catalogue available at http://www.library.ubc.ca

3.3.2 *Selection of Wildlife Species*

Wildlife species from the Kearl Lake EIA were selected for habitat suitability modeling. To ensure comparability, the same equations used to calculate habitat suitability in Kearl Lake were also used in the analysis reported here. The selection of target species is shown in Table 13. It should be noted that for some species, the habitat suitability index includes parameters with a spatial component, the latter of which requires calculation of one or more landscape metrics. For present purposes, HSIs were calculated for the 10 species without including spatial metrics. In practical terms, these HSIs then represent the most optimistic scenarios for habitat development since the inclusion of spatial metrics only serves to reduce habitat suitability (though in some cases, the HSI may remain unchanged). A spatially explicit analysis will be included in Phase II of this project.

Table 13. Wildlife species selected for habitat suitability modeling.

Species	CEMA priority level	Spatial modeling approach	Reference
Moose	1	Interspersion & ZOI disturbances	Eccles et al. (1986) Jalkotzy et al. (1990)
Fisher	1	Interspersion	Allen (1983b) Jalkotzy et al. (1990)
Lynx	1	ZOI disturbances	Imperial Oil (2005)
Canadian toad	1	Spatial explicit	Imperial Oil (2005)
Snowshoe hare	1	No	Jalkotzy et al. (1990)
Red-backed vole	1	No	Eccles et al. (1986) Jalkotzy et al. (1990)
Black bear	2	Interspersion & ZOI disturbances	Jalkotzy et al. (1990)
Beaver	2	Spatial explicit	Allen (1983a)
Ruffed grouse	2	Interspersion	Jalkotzy et al. (1990)
Pileated woodpecker	2	Nesting habitat units per area	Bonar (2001)
Cape May Warbler	2	No	Skinner (1996)
Northern goshawk	3	Nesting habitat units per area	Schaffer et al. (1999).

3.3.3 *Variables used in the Habitat Suitability Models*

Species-specific habitat suitability models are listed in Appendix 2. Most of the variables used in the habitat suitability models, however, are common for all the species and simply include modifiers that are species-specific. A description of each key variable used in the HSI models is as follows.

Canopy closure (CC): All the wildlife species for which habitat models have been developed are forest species, and therefore this variable is present in all the habitat models. CC is the percentage of open sky covered by trees at canopy level, and it is directly related to the fraction of light passing through the canopy (Alabak 1982, Martens et al. 2000).

Therefore, the light levels at the bottom of the canopy (a FORECAST output variable) can be used to calculate CC as follows:

$$CC_t = \frac{(1 - Light\ canopy\ bottom_t)}{(1 - MAX\ (Light\ canopy\ bottom))}$$

Structural stage (ST): Many wildlife species depend on a specific structural stage for shelter or food. Tree height is used as the proxy for structural stage (Table 14).

Table 14. Vegetation Structural Stages as related to vegetation type and height (Imperial Oil 2005).

Structural Stage	Dominant vegetation
Non-vegetated	barren soil
Herbaceous	Herbs, grass or shrub <1 m
Low shrub	Shrub 1 to 3 m
Tall shrub	Shrub 3 to 6 m
Pole sapling	Trees 7 to 12 m and single canopy
Young forest	Trees 7 to 12 m and diverse canopy structure, or 13 to 18 m with single canopy
Mature forest	Trees 13 to 18 m with diverse canopy, or >18 m with single canopy
Old-growth forest	Trees >18 m and stands older than 100 years

Shrub cover (SC): Many wildlife species depend on the presence of a shrub layer to produce berries and other food sources and to provide cover close to the ground. SC describes the proportion of ground covered by shrubs, and is calculated using a sigmoidal function that converts foliage biomass (a FORECAST output variable) to percent cover. The coefficients a, b, c and d are specific for each understory species.

$$SC_t = \frac{a}{(1 + e^{(b - c(Species_a\ foliagebiomass_t))})^{1/d}}$$

Species-specific canopy closure (SaCC): Many wildlife species prefer a single species or tree type (either conifer or deciduous), or a specific type of shrub. Because of a direct link between foliar biomass and canopy closure, SaCC can be calculated as the total CC (see above) modified by the fraction of total stand foliage biomass represented by that species:

$$S_aCC_t = CC_t \times \frac{Species_a\ Foliage\ Biomass_t}{Total\ Foliage\ Biomass_t}$$

Canopy / shrub height: Some species are directly affected by the height of trees and shrubs, as this variable affects their movements when looking for cover or food. This variable is directly calculated from FORECAST.

3.3.4 *How the HSIs were Applied*

Two scenarios were evaluated with respect to the calculation of HSIs for the 10 species, the pre-mining landscape, and the active and post-mine closure landscape. The HSIs were then evaluated by species and compared against each scenario, using the following methodology:

1. In the pre-mining landscape, ecosite phases (a1, b1-b4, c1, d1-d3, e1-e3) and structural stages – Low and tall shrubs (0 to 7 m, 0 to 15 years old); Pole or sapling (7 to 12 m, 30 to 60 years old); Young forest (13 to 18 m, 60 to 80 years old); Mature forest (> 18m, 80 to 100 years old); Old-growth forest (> 100 years old) – and their areal extent were obtained from EIA reports and corresponding GIS map layers.

2. A series of analysis units were created to reflect the community composition characteristic of each ecosite phase and average productivity (represented as site index)(see Beckingham and Archibald 1996). Analysis units are listed in Table 15.

3. (a) FORECAST was calibrated for each analysis unit and respective growth and development trajectories simulated for 145 years following a stand-replacing fire. (b) Output from each analysis unit was used as input to the HSI models for the 10 species and the change in HSI calculated over the 145 year time period.

4. The total area of a given analysis unit (i.e., ecosite phase) was subdivided into areas that represented the proportion of each structural stage (shrub, sapling, young forest etc …) within a given unit. See Table 16 for an example of this procedure.

5. A weighted HSI was calculated for each species, as follows. Within a given simulation year, the HSI value corresponding to a given ecosite was multiplied by its corresponding area on the pre-mining landscape (this is the weighting component). This weighted HSI represents the number of habitat units (HU; ha) created for a given species in a given year.

6. A similar procedure was employed to calculate the weighted HSI values associated with reclamation, except that (a) FORECAST runs were conducted for each ecosite phase using a 50 cm peat:mineral mix, and a medium peat decomposition rate, and (b) Reclamation occurred over discrete intervals and these were accounted for when the HUs were calculated (see Table 17). As a result of the different reclamation dates, different cohorts of the same ecosite were present simultaneously within a given calendar year, with each cohort having a different stand age and therefore a different HSI value for each wildlife species. The total number of HUs for a given species within a given time period was thus calculated by multiplying its HSI value by the number of hectares of that reclaimed ecosite.

Table 15. Analysis units used in FORECAST and representative of the Kearl Lake boreal mixedwood upland region.

Ecosite Phase	Tree species	Seedling site index	Run site index	Starting density	Seedling age	Understory functional group	Starting percent cover
a1	Jack pine	14	14	2000	3	Green alder	0.1
						Mid-seral forb	0.15
b1	Jack pine	15	16	1500	3	Green alder	0.15
	Aspen	17.5		1000	3	Mid-seral forb	0.2
b2	Aspen	17.5	16	2000	3	Green alder	0.15
						Mid-seral forb	0.2
b3	Aspen	17.5	16	1600	3	Green alder	0.15
	White spruce	15		400	3	Mid-seral forb	0.2
						Grass	0.001
b4	White spruce	15	16	800	3	Green alder	0.15
	jack pine	15		1200	3	Mid-seral forb	0.2
c	White spruce	12	14	500	3	Green alder	0.15
	jack pine	15		1500	3	Mid-seral forb	0.2
d1	Aspen	18	18	2500	3	Green alder	0.3
						Hazelnut	0.3
						Mid-seral forb	0.5

Ecosite Phase	Tree species	Seedling site index	Run site index	Starting density	Seedling age	Understory functional group	Starting percent cover
						Grass	0.1
d2	Aspen	18	18	1500	3	Green alder	0.3
	White spruce	17		1000	3	Hazelnut	0.3
						Mid-seral forb	0.5
						Grass	0.1
d3	White spruce	17	18	2500	3	Green alder	0.3
						Hazelnut	0.3
						Mid-seral forb	0.5
e1	Aspen	20	20	2500	3	Green alder	0.1
						Mid-seral forb	0.3
						Grass	0.1
e2	White spruce	18	20	1500	3	Green alder	0.1
	Aspen	20		1000	3	Mid-seral forb	0.3
						Grass	0.1
e3	White spruce	18	20	2500	3	Green alder	0.1
						Mid-seral forb	0.3
						Grass	0.1

Table 16. An illustrative example of the breakdown in the total ecosite area by phase and structural stage on the Kearl Lake mine.

Ecosite	Total ecosite area (ha)	Ecosite phase	Ecosite phase area (h)	Stage	Stage year
a	651.2	a1	117.6	Shrub	15
a	651.2	a1	27.4	Sapling	45
a	651.2	a1	96.9	Young forest	70
a	651.2	a1	233.3	Mature forest	90
a	651.2	a1	176.0	Old-growth	100
b	1,317.50	b1	237.9	Shrub	15
b	1,317.50	b1	55.5	Sapling	45
b	1,317.50	b1	196.1	Young forest	70
b	1,317.50	b1	472.0	Mature forest	90
b	1,317.50	b1	356.1	Old-growth	100
b	1,978.00	b2	357.1	Shrub	15
b	1,978.00	b2	83.3	Sapling	45
b	1,978.00	b2	294.4	Young forest	70
b	1,978.00	b2	708.6	Mature forest	90
b	1,978.00	b2	534.6	Old-growth	100

Table 17. Area reclaimed (ha) by ecosite phase and reclamation year for the Kearl Lake mine footprint.

Ecosite phase	Reclamation event (year) 2016	2026	2031	2036	2041	2046	2051	2056	2061	TOTAL[1]
a1	647.4	-	41.3	547.8	328.3	883.2	279.1	141.5	736.6	3605.1
b1-b4	29.4	-	41.3	502.6	82.4	580.7	271.9	141.5	610.3	9040.8
c	-	-	2.9	-	-	-	-	-	-	2.9
d1-d3	105.2	469.9	214.1	-	91.7	-	1.5	-	102.4	2846.4
e1-e3	-	-	0.3	-	-	310.7	103.9	264.7	578.2	3773.4
TOTAL	1080.7	1409.7	852.8	2558.2	933.1	4138.1	1683.0	1501.4	5219.3	19376.4

[1] Areas apply to each individual phase. Totals are therefore the sum for each phase within a given ecosite.

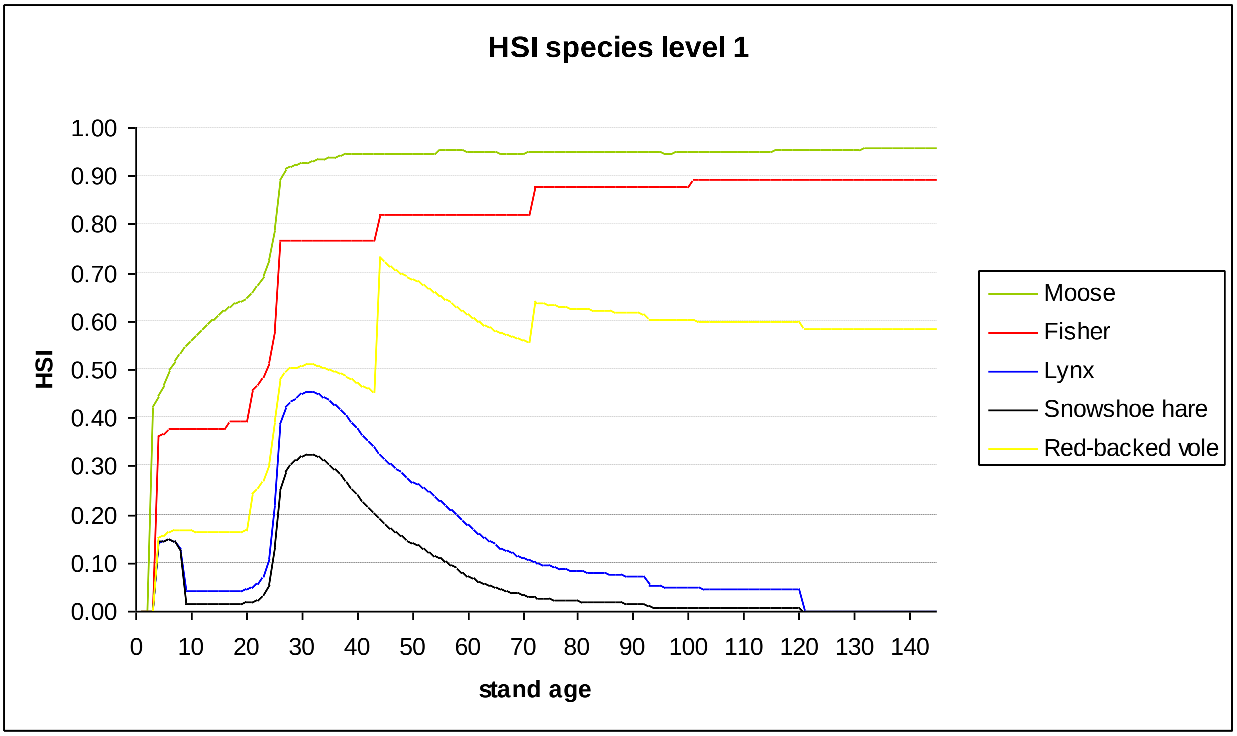
3.4 Results and Discussion

3.4.1 *HSIs by Ecosite Phase*

There were considerable differences among species in HSI values for a given ecosite phase. Figure 9 illustrates these differences using the a1 phase as an example (see Appendix 3 for graphs of all phases). For many species, their HSI values increased with stand age in conjunction with development of structural attributes to which they were correlated. Many of the HSI equations are comprised of step functions (see Methods) and this is often reflected in the trends in the HSI values. For species such as snowshoe hare, their dependence on understory plants as a food source usually resulted in an initial increase in the HSI, followed by a decline and then an increase in very old stands (Figure 9). This trend is consistent with the fact that understory species are abundant during stand initiation, decline during canopy closure, and then increase in older stands as the canopy senesces and light conditions increase within the stand. Snowshoe hares are an important food source for lynx and the HSI for the latter incorporates the HSI value for hares. Consequently, there is a consistent and close correlation between the HSI values for these species. The broad variation among species in their HSI values (Figure 9; see also Appendix 3) suggests that reclamation practices could be targeted towards the habitat requirements of one particular wildlife species by preferentially reclaiming more favorable ecosite phases. Conversely, a broad range of ecosite phases is necessary to promote a wide suite of biodiversity habitat on the reclaimed landscape, recognizing that even if suitable varied habitat is available, there is no guarantee of its use.

3.4.2 *Habitat Units by Ecosite and Reclamation Period*

The number of habitat units (HUs) for each species is calculated by determining its HSI value corresponding to a given ecosite multiplied by the corresponding reclaimed area within a given simulation year (see Methods). The total HUs created for a particular species therefore depends on (a) how much habitat is created by reclaiming to a given ecosite (or ecosite phase; see Appendix 3), and (b) how much of that ecosite is reclaimed over time (as per, for example, Table 17). For some species (moose, for example), the total number of HUs increased monotonically (Figure 10, top; see Appendix 4 for all species); this relationship is a direct reflection of the increase in moose HSI with time (Figure 9) and the relatively simple relationship between HU development at each reclamation event (Figure 10, bottom). For lynx, in contrast, the total number of HUs was much less than for moose (Figure 11, top) and the overall pattern of development was more complex (Figure 11, bottom). From a comparative perspective, the developing reclamation landscape on the Kearl Lake mine appears to provide adequate habitat for certain species such as moose, fisher, and black bear, largely because suitable habitat can be created across a broad range of ecosite phases (Appendix 3). For species in which habitat is generally more difficult to create (snowshoe hare, lynx, Cape May warbler, northern goshawk; see Appendix 3), the total amount of HUs could be enhanced by increasing the area reclaimed to those ecosite phases that are relatively more favorable (e2 and e3, for example, in the case of lynx; see Appendix 3 Figures A3-11 and A3-12).



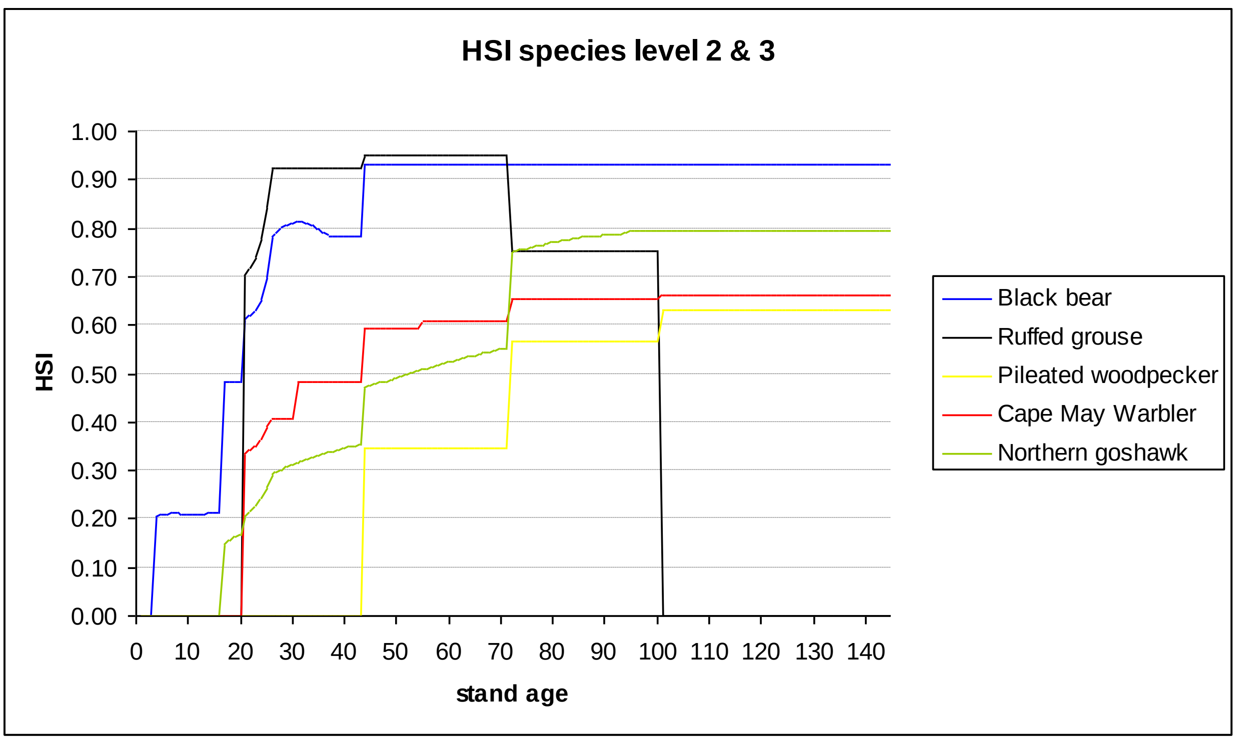
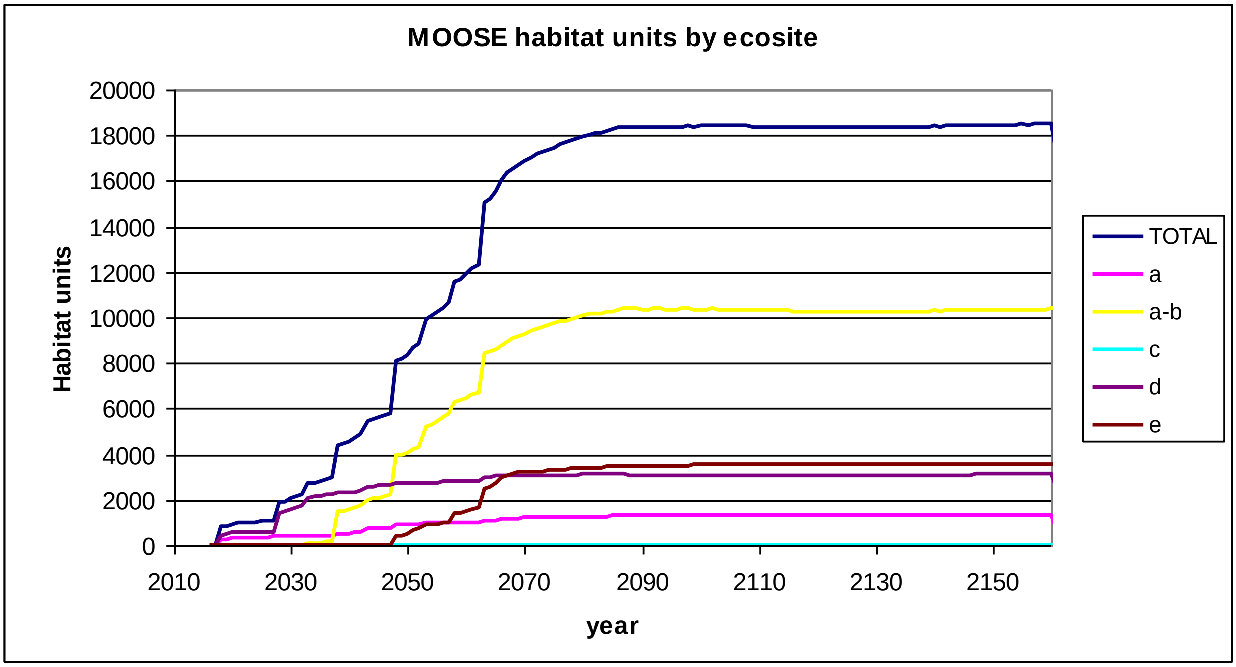


Figure 9. HSI values by stand age for ecosite a (= ecosite phase a1).



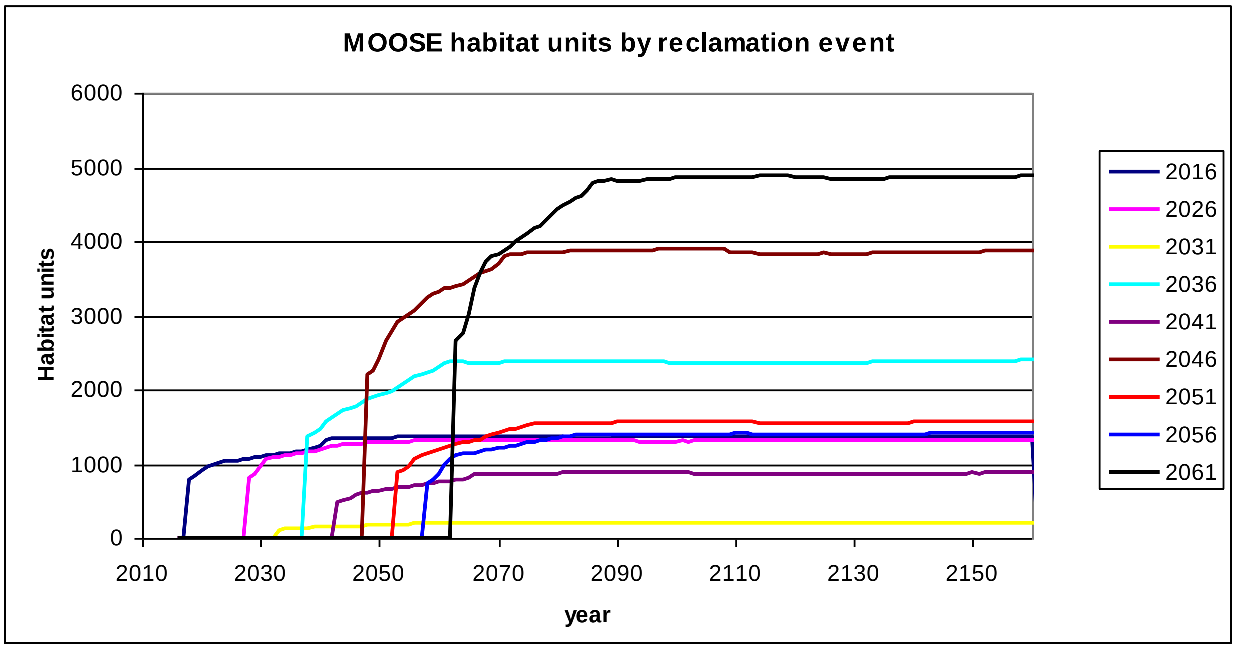


Figure 10. Habitat units (ha) for moose by ecosite (top) and timing of reclamation (calendar year; bottom).

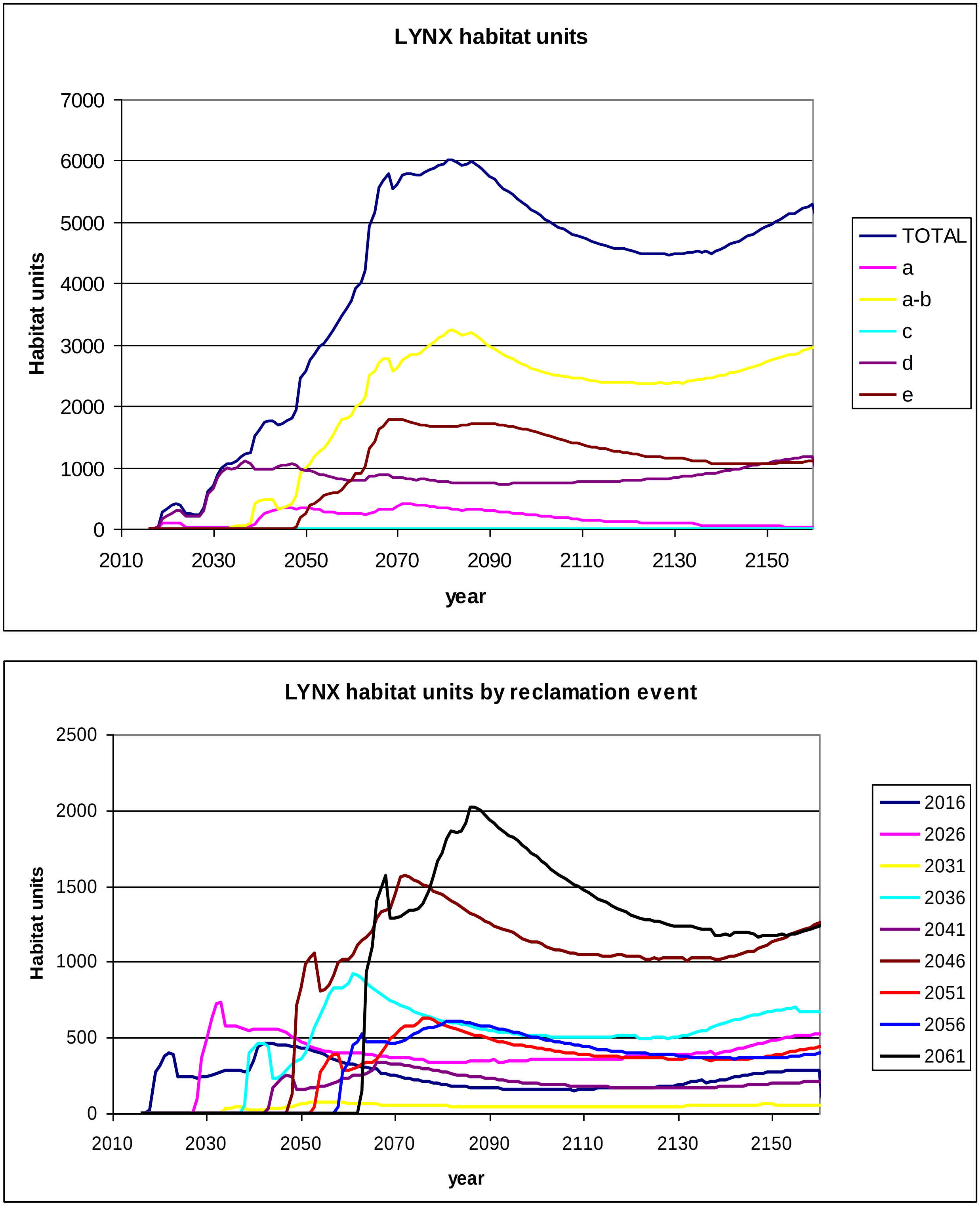


Figure 11. Habitat units (ha) for lynx by ecosite (top) and timing of reclamation (calendar year; bottom).

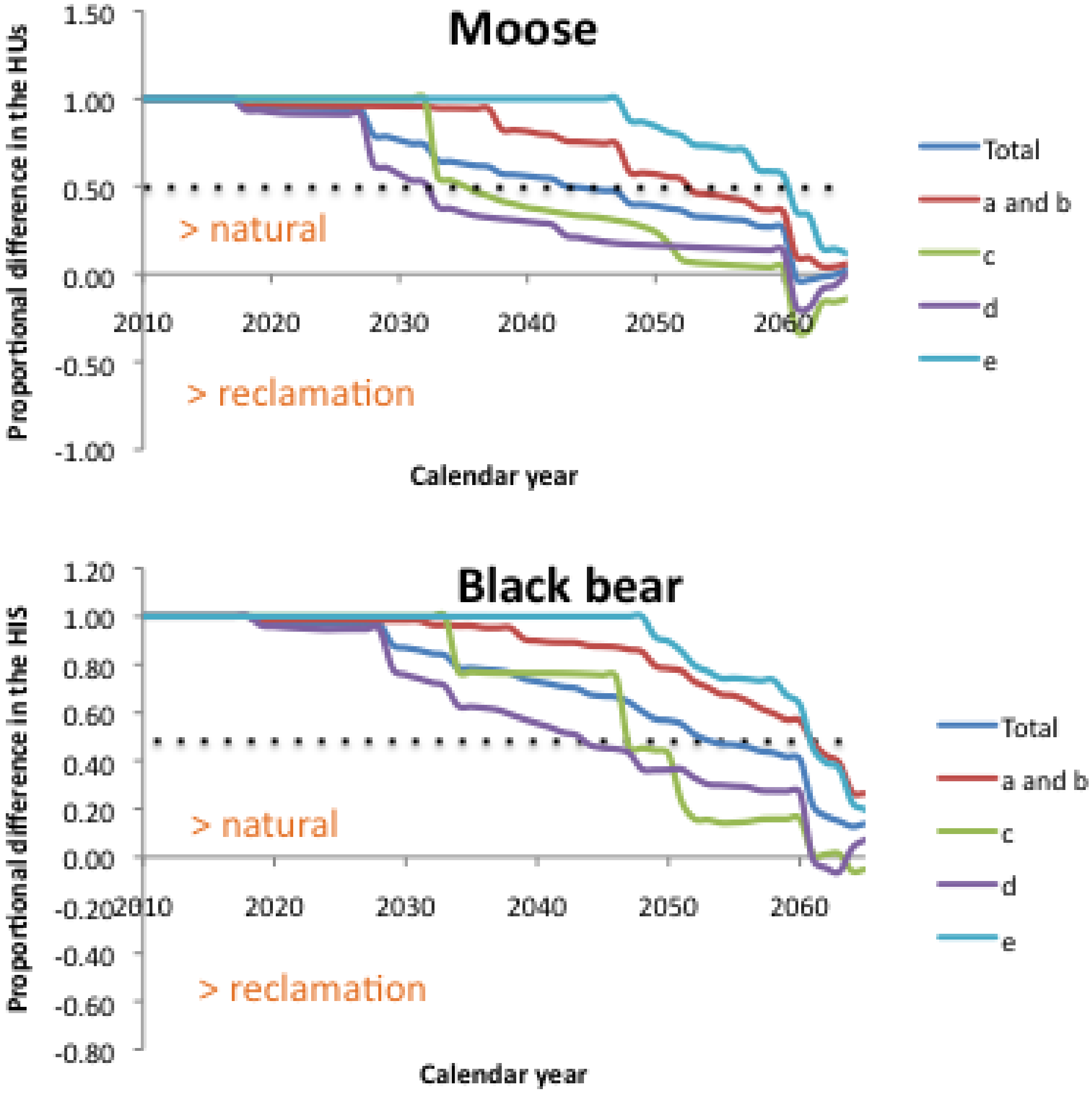
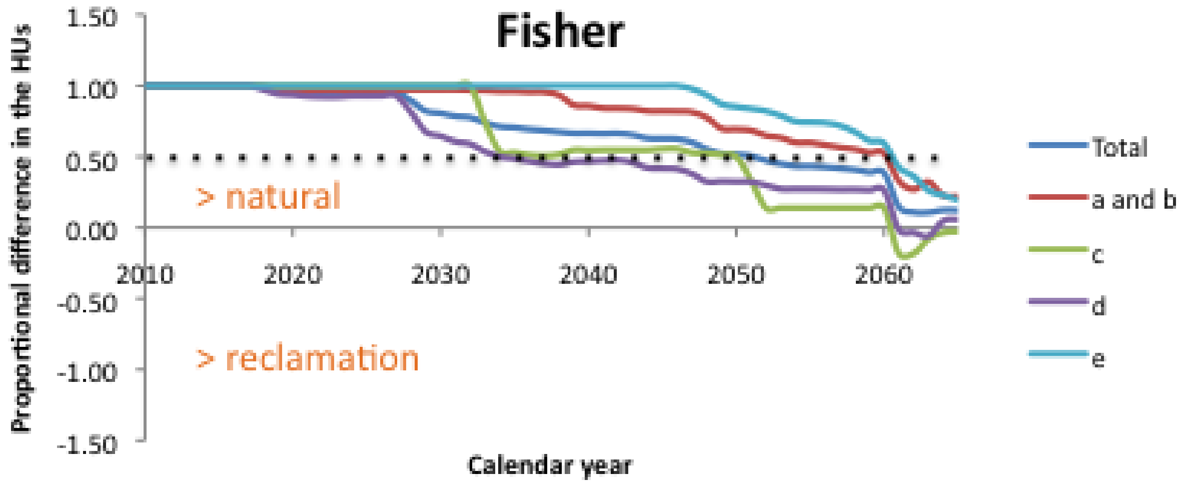


Figure 12. Relative difference in habitat units (HUs; ha) for moose and black bear between the natural landscape and the Kearl Lake mine footprint for ecosites a-e, from the beginning of mining (2010) to mine closure (2065).

HUs greater than zero indicate more habitat in the natural landscape; values less than zero indicate more habitat on the reclaimed mine area. The horizontal line denotes a 50% recovery in the reclaimed versus the natural landscape.



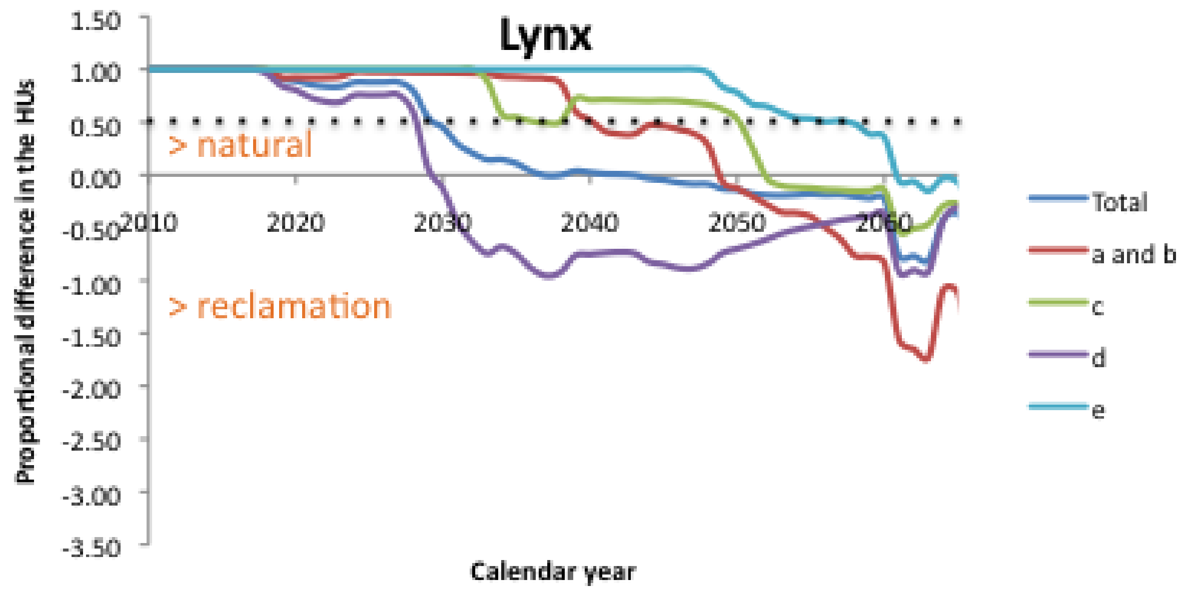
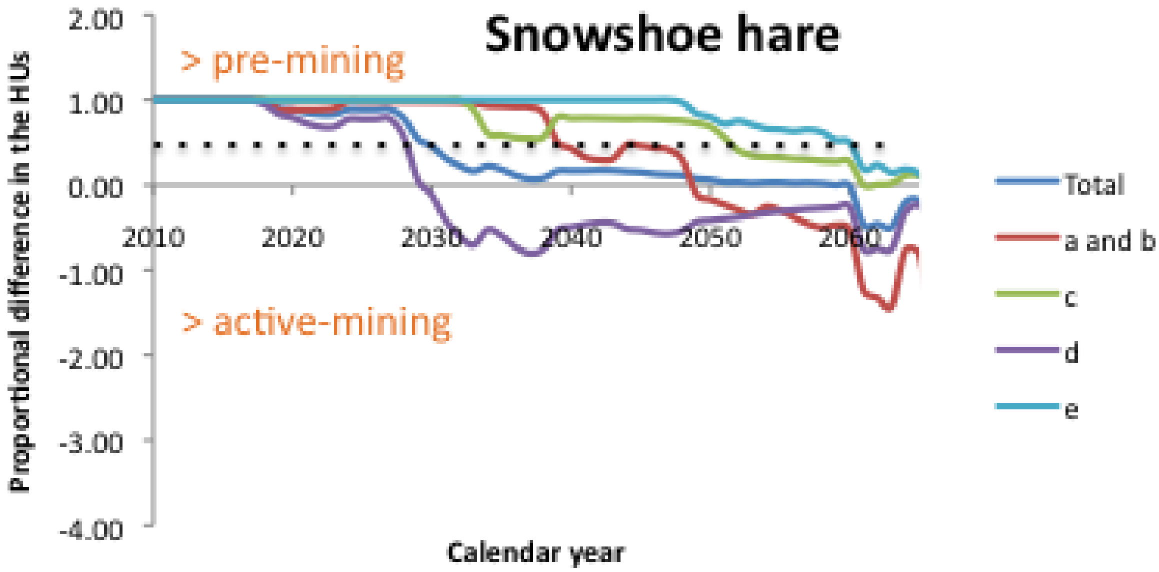


Figure 13. Relative difference in habitat units (HUs; ha) for fisher and lynx between the natural landscape and the Kearl Lake mine footprint for ecosites a-e, from the beginning of mining (2010) to mine closure (2065).

HUs greater than zero indicate more habitat in the natural landscape; values less than zero indicate more habitat on the reclaimed mine area. The horizontal line denotes a 50% recovery in the reclaimed versus the natural landscape.



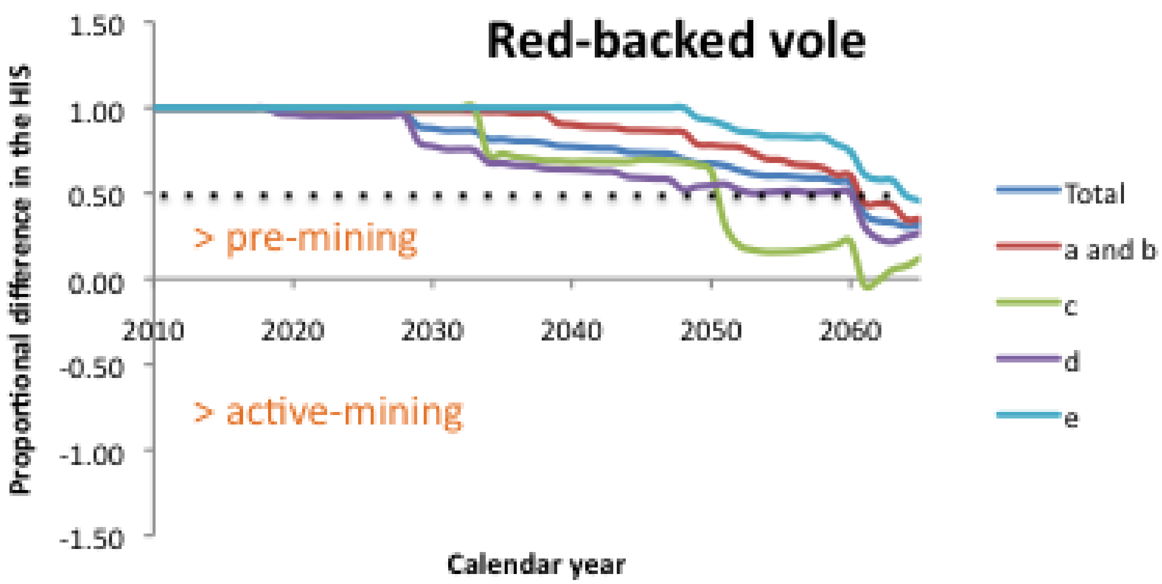


Figure 14. Relative difference in habitat units (HUs; ha) for snowshoe hare and red-backed vole between the natural landscape and the Kearl Lake mine footprint for ecosites a-e, from the beginning of mining (2010) to mine closure (2065).

HUs greater than zero indicate more habitat in the natural landscape; values less than zero indicate more habitat on the reclaimed mine area. The horizontal line denotes a 50% recovery in the reclaimed versus the natural landscape.

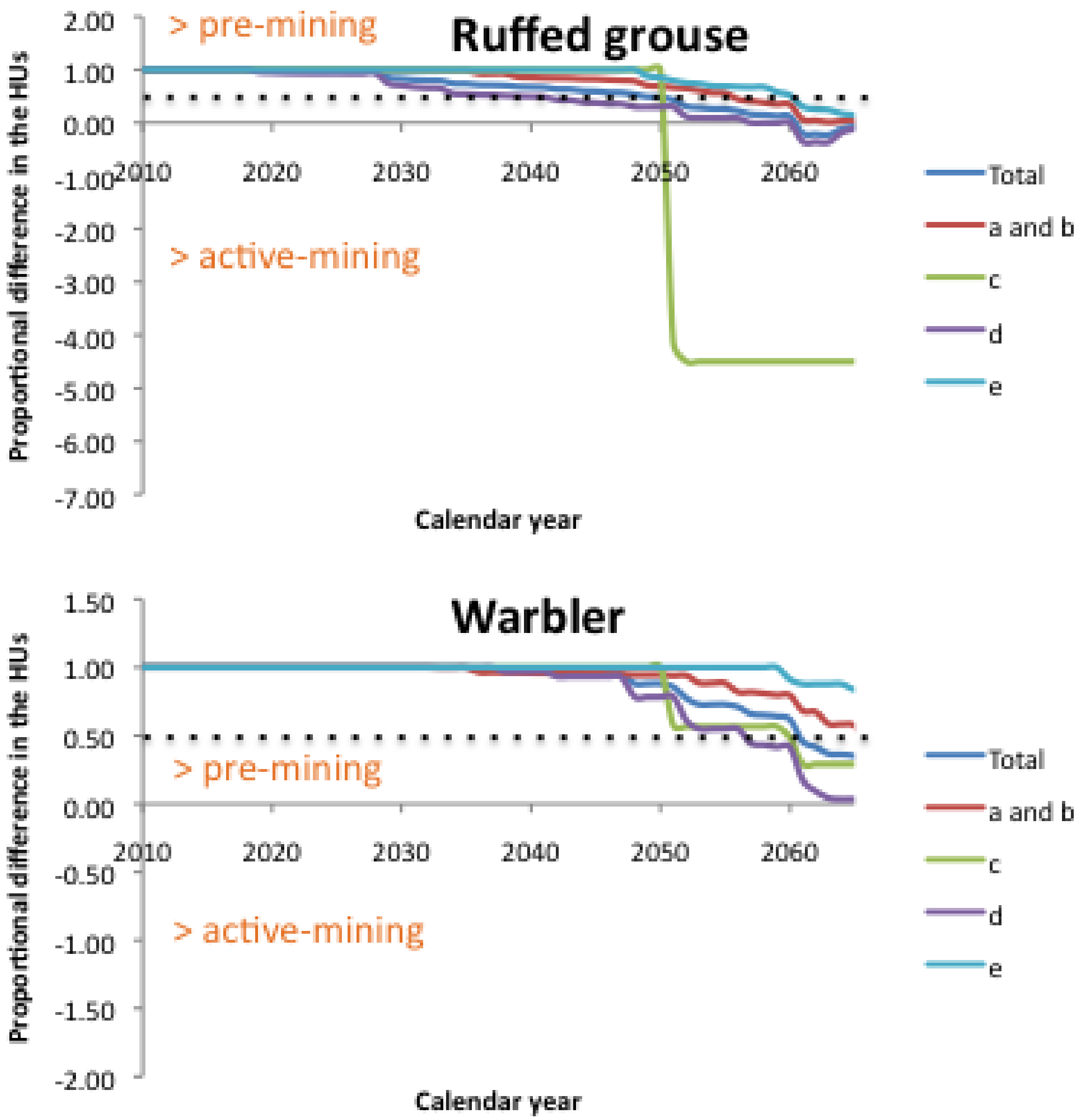


Figure 15. Relative difference in habitat units (HUs; ha) of ruffed grouse and Cape May warbler between the natural landscape and the Kearl Lake mine footprint for ecosites a-e, from the beginning of mining (2010) to mine closure (2065).

HUs greater than zero indicate more habitat in the natural landscape; values less than zero indicate more habitat on the reclaimed mine area. The horizontal line denotes a 50% recovery in the reclaimed versus the natural landscape.

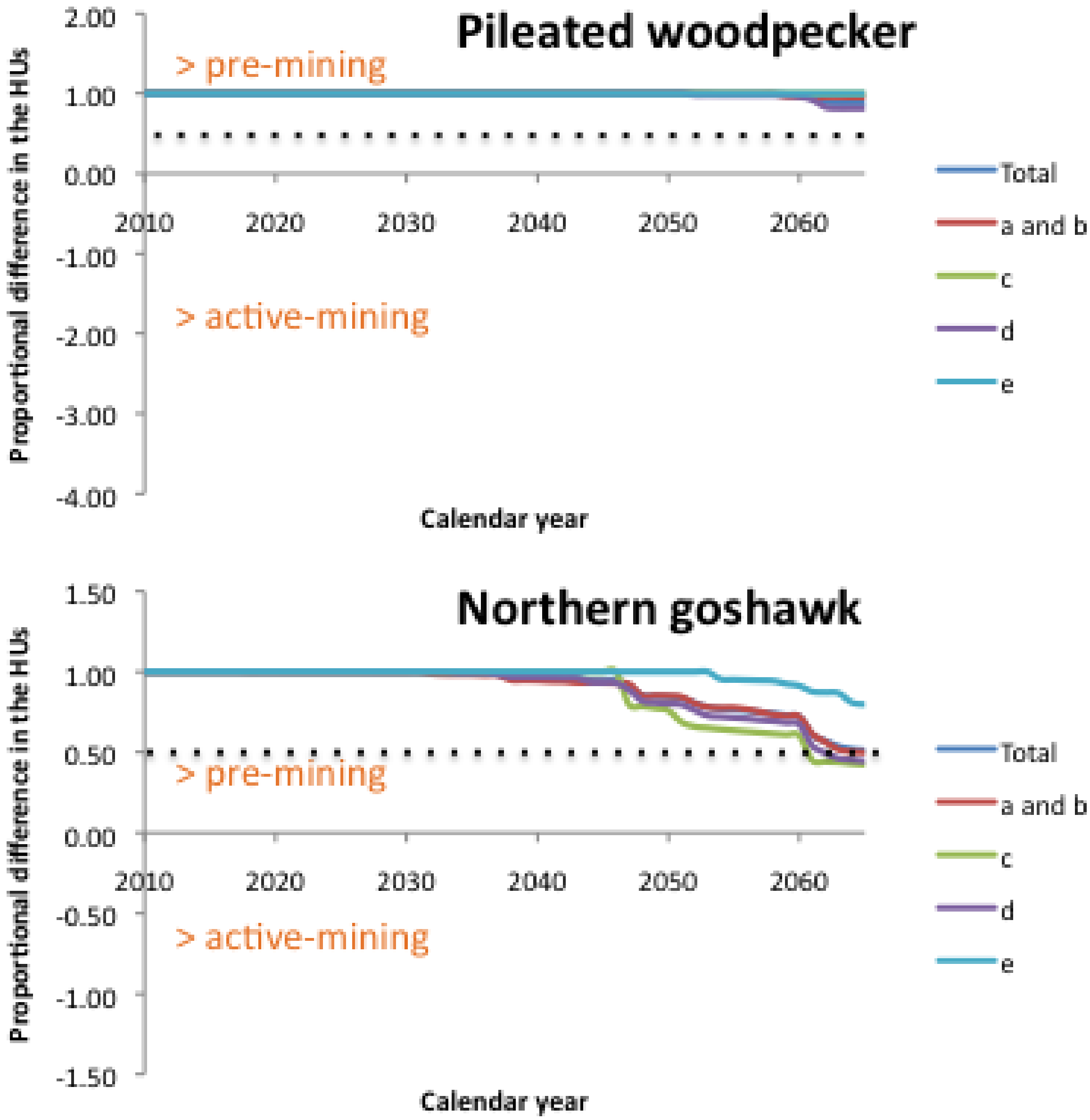


Figure 16. Relative difference in habitat units (HUs; ha) of pileated woodpecker and northern goshawk between the natural landscape and the Kearl Lake mine footprint for ecosites a-e, from the beginning of mining (2010) to mine closure (2065).

HUs greater than zero indicate more habitat in the natural landscape; values less than zero indicate more habitat on the reclaimed mine area. The horizontal line denotes a 50% recovery in the reclaimed versus the natural landscape.

3.4.3 *Comparison of HSIs between the Natural and Associated Mine Footprint*

Typically, the initiation of mining activities on a given lease results in the removal of essentially all ecosystems within the mine footprint. In the case of Kearl Lake, this is an area of close to 30,000 ha which, at least temporarily, contains no habitat capable of supporting healthy wildlife populations. A well-executed reclamation program has the potential to restore suitable habitat on the mine footprint but this occurs only progressively. A key question then is the extent to which progressive reclamation, as specified within the Kearl Lake approval plans, is effective in restoring habitat relative to what existed on the mine footprint prior to mining, and over what time period?

This question can be addressed by comparing habitat development for each species on the reclaimed mine footprint relative to what would have occurred on the natural landscape had it not been disturbed by mining. Results for each species are presented in Figures 12 to 15. With the exception of lynx (Figure 13) and snowshoe hare (Figure 14), the number of HUs created through reclamation did not approach equivalence with the unmanaged landscape until very close to the mine closure date, a period of about 55 years. This was not, however, the case for the pileated woodpecker. These woodpeckers are heavily reliant upon old growth forests (see Appendix 2) and an insufficient time had elapsed for any reclaimed site to develop this age class or its associated structural attributes. For lynx and snowshoe hare, the number of HUs created in d and a-b ecosites exceeded that which would have been present on the natural landscape, had mining not occurred. In the case of hare, this species is heavily dependent upon the understory for browse (see Appendix 2). Understory species tend to be abundant immediately after stand-replacing disturbance but then decline thereafter as forests age and light levels reach critically low levels. In the unmanaged landscape, disturbance events were much less frequent than in the reclaimed landscape. The latter was thus populated by much younger stands thereby favoring understory growth and hence, hare habitat suitability. Snowshoe hares are a staple food item for lynx (see Appendix 2). As a result, lynx habitat suitability was strongly related to the trends observed for snowshoe hare. These latter species also illustrate the point (see section 3.2) that with careful planning, reclamation practices could be targeted to creating ecosites that promote suitable habitat for desired species beyond that typically expected in the natural landscape.

Despite the fact that for a majority of the 10 species considered in this analysis, reclamation activities can generate HUs prior to mine closure, the total amount of available habitat during the period of active mining at Kearl Lake is generally low. Under the reclamation plan described in the Kearl Lake EIA an average of 37.5 years is required following mine initiation before the number of HUs reaches 50% of the level that would have been present had the mine not been developed (Table 18). More than 50 years will have elapsed before a 100% recovery in HUs is achieved (Table 18). There is also considerable variation in recovery rates among species. Lynx and snowshoe hare HUs, for example, reach 50% recovery in only 15 years; in contrast, 65 and 50 years are required for pileated woodpecker and northern goshawk, respectively. All other species lie somewhere in between these extremes. When these recovery rates are considered in conjunction with the overall mine footprint (in this case, almost 30,000 ha), it suggests that the impact of the operation is not trivial with respect to habitat loss. It should be noted that this analysis constitutes an optimistic assessment of habitat availability because many of the spatial parameters associated with anthropogenic disturbance that comprise a given HSI were not explicitly considered in its calculation. In addition, inputs into the HSI calculations from projections of forest development made with the FORECAST model were derived without explicit consideration of any potential negative consequences associated with future climate change. This protocol thus represents a set of 'basecase' scenarios against which scenarios that include climate change and the spatial configuration of habitat and human disturbance will be compared in the next phase of the project. Finally, to properly evaluate the impact of the Kearl Lake operation on habitat availability, this project must be evaluated within the context of all existing and proposed mine leases, other types of industrial activity, as well as areas not subject to anthropogenic disturbance. This regional-level analysis will be addressed in the third phase of the project.

Table 18. Development of total habitat units to levels of 50% and 100% of the natural landscape condition for 10 wildlife species.

Species	Years to 50 % recovery	Years to 100 % recovery
Moose	30	50
Black bear	40	55
Fisher	35	55
Lynx	15	25
Snowshoe hare	15	40
Red-backed vole	45	55
Ruffed grouse	35	45
Cape May Warbler	45	55
Pileated woodpecker	65	75
Northern goshawk	50	55
Mean (± SD)	37.5 ± 13.5	51 ± 11

3.5 Conclusions

1. There is a 37-year window following mine operation when upland habitat suitability is very poor on the mine footprint (an area that encompasses almost 30,000 ha).
2. Habitat suitability recovers relatively quickly thereafter; 50 years after mine operation, 4 out of 10 species have a 100 % suitability index, and this increase to 9 out of 10 species 55 years after mine operation.
3. The overall amount and pattern of recovery in habitat depends on how much upland is reclaimed relative to the original (pre-mining) landscape.
4. Deviations in the post-mining distribution of ecosite phases relative to the pre-mining landscape could have significant implications for the habitat suitability of particular species, either positively (more habitat is created) or negatively.
5. The broad variation among species in their HSI values suggests that reclamation practices could be targeted towards the habitat requirements of one particular wildlife species by preferentially reclaiming more favourable ecosite phases. Conversely, a broad range of ecosite phases is necessary to promote a higher degree of biodiversity on the reclaimed landscape.
6. When habitat recovery rates on reclaimed sites are considered in conjunction with the overall mine footprint, it suggests that the impact of the operation is not trivial with respect to habitat loss. It should be noted that this analysis constitutes an optimistic assessment of habitat availability because many types of anthropogenic disturbance were not included in this phase of the project. Inclusion of disturbance would tend to depress habitat suitability, at least for some species. In addition, inputs into the HSI calculations from the FORECAST model were derived without explicit consideration of any potential negative consequences to forest development associated with future climate change.

4 A RISK ANALYSIS OF THE POTENTIAL FOR DEVELOPMENT OF WATER STRESS IN YOUNG RECLAMATION PLANTATIONS AT THE KEARL LAKE MINE

4.1 Summary

The development of ecologically viable reclamation strategies and methodologies in the Oil Sands region can be a difficult undertaking considering the logistical challenges of constructing soil covers capable of providing both the hydrological and nutritional characteristics required for the establishment of self-sustaining, productive forest ecosystems. To examine the potential for the development of water stress in proposed reclamation plantations within the Kearl Lake mining area, a risk analysis was conducted for different species and ecosite combinations using the stand-level forest hydrology model ForWaDy. The risk analysis was designed to evaluate the probability of high levels of water stress developing in young plantations of white spruce, trembling aspen, and jack pine established on different ecosites as a function of soil texture and

slope position. Each species and soil type combination was simulated for a 25-year period using historical climate data from the Fort McMurray weather station. Annual summaries of simulated water stress (expressed as a Transpiration Deficit Index; TDI) during the growing season were used to derive probabilities of exceeding a range of water stress thresholds.

Spruce was the most likely species to experience high TDI levels (greater than 0.3). In addition, it was the only species to reach TDI levels greater than 0.6 during the 25-year simulation period. Jack pine, in contrast, was the least likely to experience high TDI levels and did not exceed levels of 0.5 during any year; the remaining species were intermediate between the spruce and pine. The probability of exceeding TDI thresholds was consistently greater in an a-b ecosite grouping (representing dry, nutrient poor sites) relative to a d-e grouping (moist, nutrient-rich sites). Differences among the two ecosite groupings were relatively small, however. The difference between the two groupings would be greater if not for the 50 cm peat layer that is applied to each site as a rooting substrate, and which alone constitutes 70% to 80% of the water holding capacity of the total soil profile.

The probabilities reported here are based on the simulated response of the tree-soil combinations to the past 25 years of climate data (1982 to 2006). These years reflect the current climate but are not likely to be representative of future climate conditions predicted for the region from Global Circulation Models. An exploration of the impact of climate change on water stress and its implications for overall growth and the associated development of structural habitat elements will be conducted in Phase II of the project.

4.2 Introduction

The development of ecologically viable reclamation strategies and methodologies in the oil sands region can be a difficult undertaking considering the logistical challenges of constructing soil covers capable of providing both the hydrological and nutritional characteristics required for the establishment of self-sustaining, productive forest ecosystems. Moreover, the onset and acceleration of shifting climate regimes in the region could significantly increase the risk of plantation failure or poor performance. Output from regional climate change analyses using Global Circulation Models shows a trend of decreasing growing season precipitation coupled with warming temperatures (Barrow and Yu 2005). Furthermore, analysis of factors influencing the development of water stress in young reclamation plantations conducted for the Cumulative Environmental Management Association (Seely and Welham 2010) showed that the frequency of dry summers will have a strong impact on the development of water stress and that the use of deeper covers alone will not effectively mitigate the problem.

To elucidate the issue of climate change and its relation to ecosystem productivity within the context of reclamation, it is useful to consider the temporal patterns of risk associated with forest ecosystem resilience. The mechanisms associated with plantation failure or poor performance change during the process of stand growth and development (Figure 17). In the establishment phase, plantations are most vulnerable to drought stress because their root systems are not fully developed and access to stored soil water is limited. In addition, there can be a high degree of competition from minor vegetation for limited water resources during this period. Nutrient deficiencies, in contrast, tend to develop later beginning when the forest canopy is rapidly expanding and approaching canopy closure, and uptake demands are increasing. This problem is exacerbated by the fact that nutrient availability during this stage tends to be relatively low since any nutrient flush following the initial soil disturbance (termed the assart flush) has typically receded. As the stand continues to develop, the risk of nutrient deficiency tends to subside because more nutrients become available from within-ecosystem nutrient cycling and tree uptake demand is reduced through the process of internal cycling (retention of nutrients in perennial tissues prior to litterfall). As a consequence of these dynamics, ecosystem resilience – defined as the capacity of an ecosystem to maintain its structure and function in the presence of stress or following disturbance – tends to increase in a sigmoidal pattern from stand establishment through maturity (Figure 17). This is particularly true for an ecosystem recovering from a severe disturbance as is the case in oil sands reclamation.

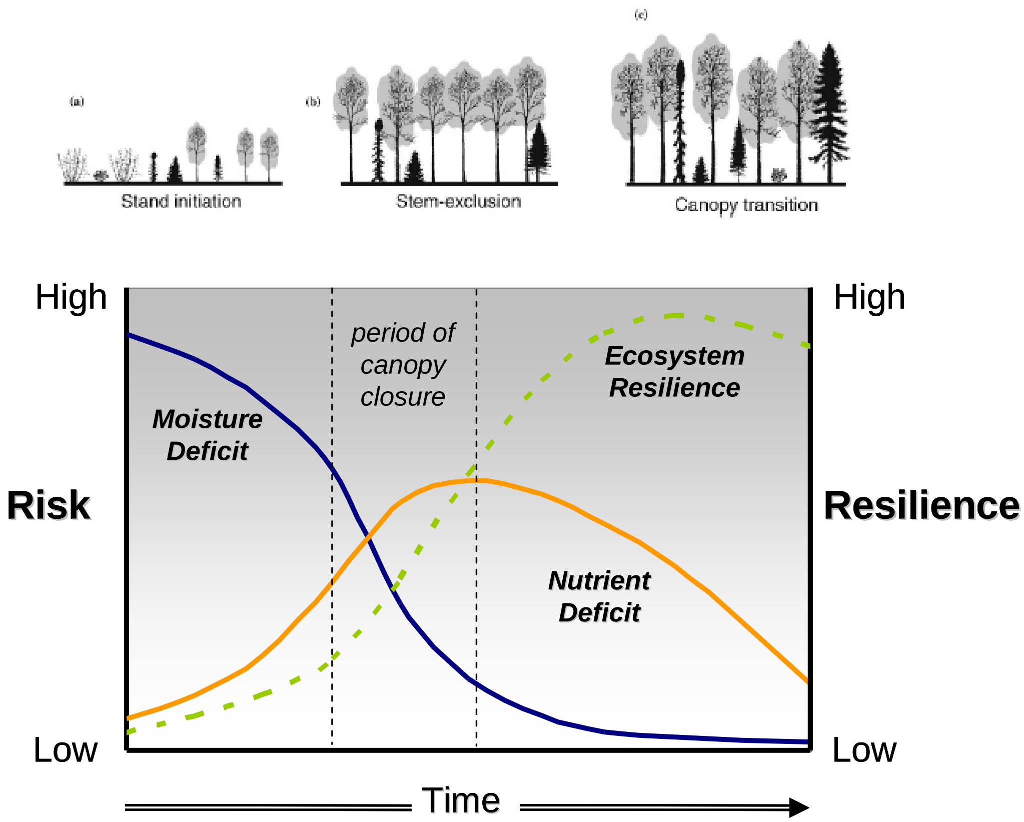


Figure 17. A graphical representation of the temporal patterns of risk of plantation failure or poor performance associated with moisture and nutrient deficits from the time of stand establishment to maturity.

A general trend in ecosystem resilience (as defined in the text) is also shown. Notice that the risk of nutrient deficiency reaches its peak during the period of canopy closure.

To examine the potential for the development of water stress in proposed reclamation plantations within the Kearl Lake mining area, a risk analysis was conducted for different species and ecosite combinations using the stand-level forest hydrology model ForWaDy. The risk analysis was designed to evaluate the probability of high levels of water stress developing in young plantations of white spruce, trembling aspen, and jack pine established on different ecosites determined as a function of soil texture and slope position.

4.3 Methods

4.3.1 *Description of ForWaDy Model*

ForWaDy (Forest Water Dynamics) is a vegetation-oriented, forest hydrology model in which potential evapotranspiration (PET) is calculated using an energy balance approach based on the widely used Priestly-Taylor equation. Incoming radiation is partitioned among vertically stratified canopy layers (vegetation type) and the forest floor to drive actual evapotranspiration (AET) calculations. ForWaDy can be used as a stand-alone decision-support tool for evaluating the hydrological interactions between soil, vegetation and climate. It is structured for portability, with minimum soil data requirements and parameter values that are relatively easy to estimate. The model has a representation of the soil physical properties dictating moisture availability, storage, and infiltration. A schematic illustration of the model structure employed in ForWaDy is shown in Figure 18. A detailed description of ForWaDy is provided in Seely et al. (1997).

Water stress in ForWaDy is calculated as a transpiration deficit index (TDI), based on the following equation:

TDI = (CanT_Total - CanTActual)/CanT_Total

where:

CanT_Total = energy limited transpiration: f (leaf area index, intercepted short-wave radiation, canopy albedo, and canopy resistance)

CanT_Actual = actual tree transpiration: f (CanT_Total, root occupancy, available soil moisture)

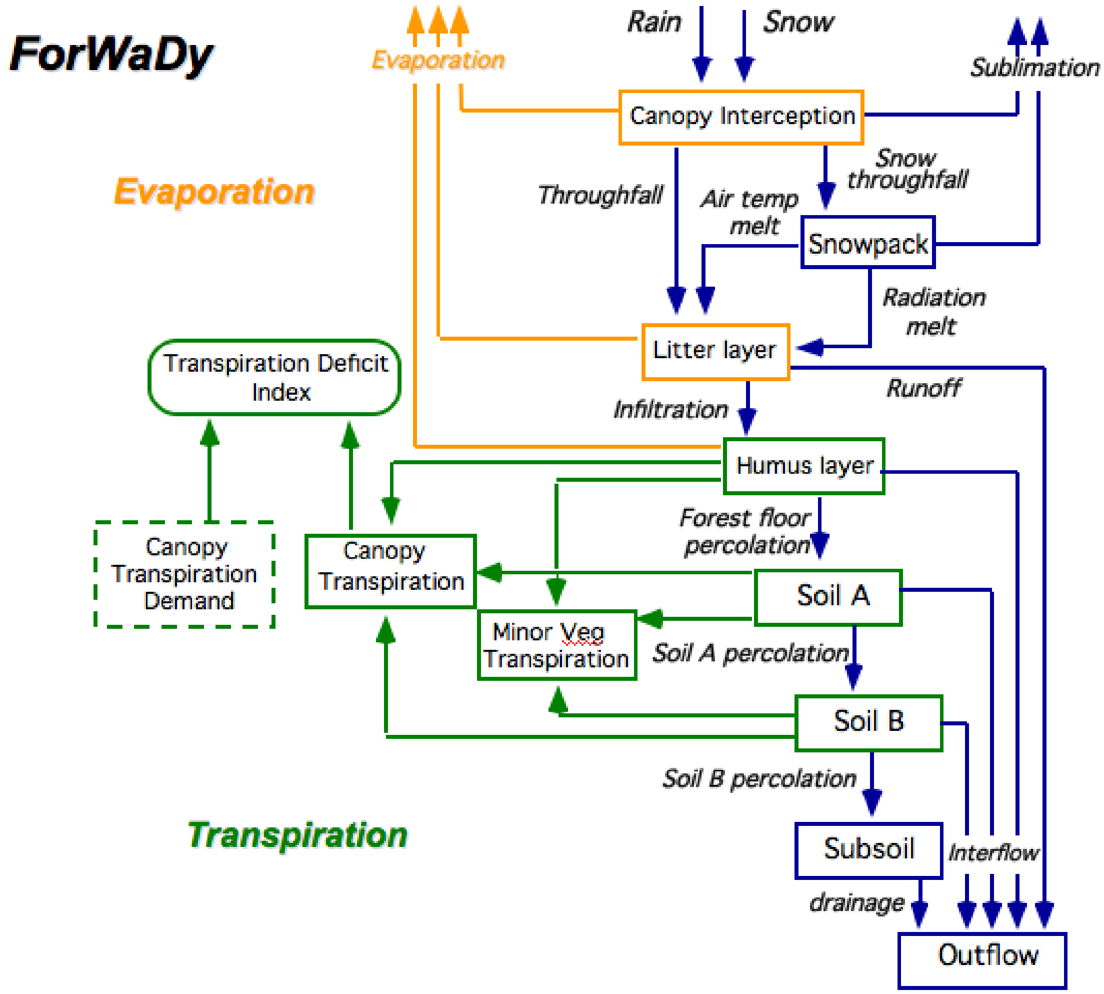


Figure 18. Schematic illustration of the structure of ForWaDy indicating the various flow pathways and storage compartments represented in the model.

4.3.2 *Risk Analysis: Application of ForWaDy*

The ForWaDy model was employed to simulate the development of water stress under different climate, soil and vegetation conditions. A combination of tree species (white spruce, trembling aspen, and jack pine) and two ecosite groups, a-b (representing dry, nutrient-poor sites) and d-e (moist, nutrient-rich sites), was used as a framework to represent the range of reclamation conditions proposed for the Kearl Lake mine site based on the environmental impact assessment completed for the proposed mine (Imperial Oil 2005). Ecosites were grouped based on similarities in underlying soil texture and slope position. In all cases soils were assumed to be reclaimed using a peat-mineral mix cover 50 cm in depth. Parameters used to simulate the soil characteristics of the different ecosite groups in ForWaDy are shown in Table 19. Likewise, the vegetation parameters used to simulate the different tree species and minor vegetation in ForWaDy are shown in Table 20. Leaf area and rooting values were established to reflect relatively young stands (e.g., 15 to 25 years of age). Vegetation parameters were derived from published sources.

Table 19. Soil parameters used to characterize the different ecosite groups simulated in ForWaDy.

Variable	**Ecosite Group**	
	a-b	**d-e**
Depth of peat layer (cm)	50	50
Bulk density peat	0.25	0.25
Peat porosity	0.54	0.54
Peat field capacity θ*	0.35	0.35
Depth soil A (cm)	35	35
Soil A texture class	sand	loam
Clay content (volumetric proportion)	0.06	0.175
Soil A field capacity θ	0.13	0.28
Mineral soil porosity (volumetric proportion)	0.39	0.45
k** (proportion)	0.9	0.1

* θ represents volumetric water content and ranges from 0 to 1.

**Parameter regulating the rate of drainage (soil water above field capacity) from the bottom of the Soil A layer.

Table 20. Vegetation parameters used to characterize the different tree species and minor vegetation simulated in ForWaDy.

	Spruce		**Aspen**		**Pine**		**Minor Vegetation**	
Variable	**a-b**	**d-e**	**a-b**	**d-e**	**a-b**	**d-e**	**a-b**	**d-e**
LAI / Percent Cover*	0.9	1.1	0.8	0.9	0.8	0.9	50%	50%
Canopy resistance (proportion)	0.25	0.25	0.1	0.1	0.4	0.4	0.1	0.1
Rooting depth (cm)	85	85	85	85	85	85	85	85
Root occupancy peat layer (proportion)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Root occupancy soil layer (proportion)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Peat Permanent Wilting point θ	0.15	0.15	0.135	0.135	0.12	0.12	0.12	0.12
Soil A permanent wilting point θ	0.08	0.17	0.07	0.16	0.06	0.15	0.06	0.15

*Leaf Area Index (LAI) is used for the simulation of trees while percent cover is used for minor vegetation.

Each tree species and soil type combination was simulated for a 25-year period using historical climate data from the Fort McMurray weather station. The climate data spanned years 1982 through 2006 and included daily data for mean air temperature, minimum air temperature, maximum air temperature, total precipitation, and snow fraction. Daily solar radiation data (required for ForWaDy) were simulated based upon latitude, elevation and an estimation of atmospheric transmissivity (derived from the difference between daily min and max air temperature) using a solar radiation model based on the model published by Nikolov and Zeller (1992).

Annual summaries of simulated water stress (TDI) during the growing season were recorded for each tree species and soil type combination and used to derive probabilities of exceeding particular water stress thresholds.

4.4 Results and Discussion

The probability of exceeding water stress thresholds in a given year is shown for different species grown in the a-b and d-e ecosite groups in Figures 19 and 20, respectively. The TDI thresholds range from 0.3 to 0.6. A TDI value of 0.3, for example, indicates that the tree was unable to meet 30% of its energy-limited transpiration demand; trees subject to this level of water stress are likely to experience significant reductions in annual growth (see Seely and Welham 2010). Transpiration deficits of 0.4 and above lead to further reductions in growth and in some cases, mortality, particularly if high water stress years occur consecutively.

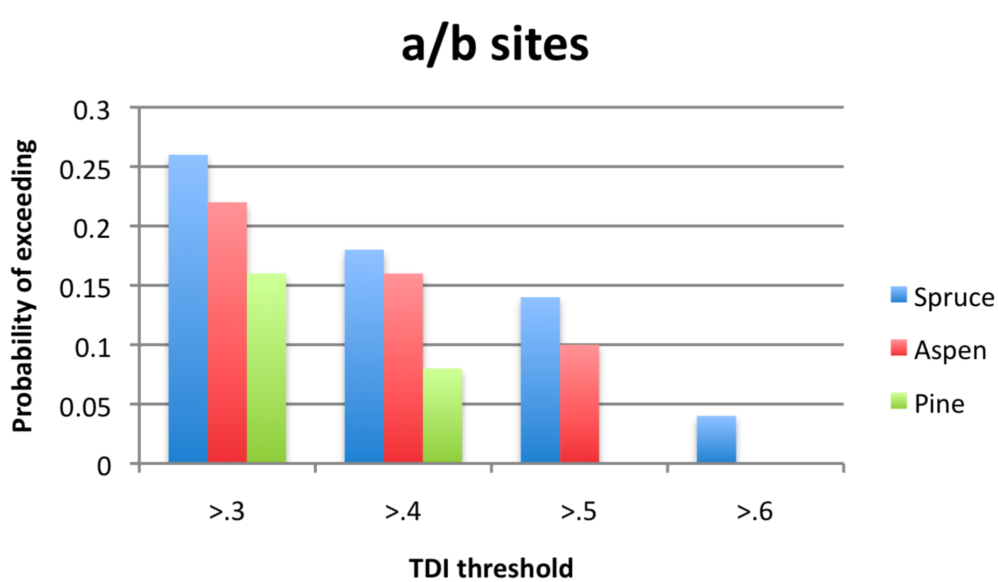


Figure 19. The probability of exceeding threshold levels of water stress as indicated by transpiration deficit index (TDI) for each species planted in an a-b ecosite type.

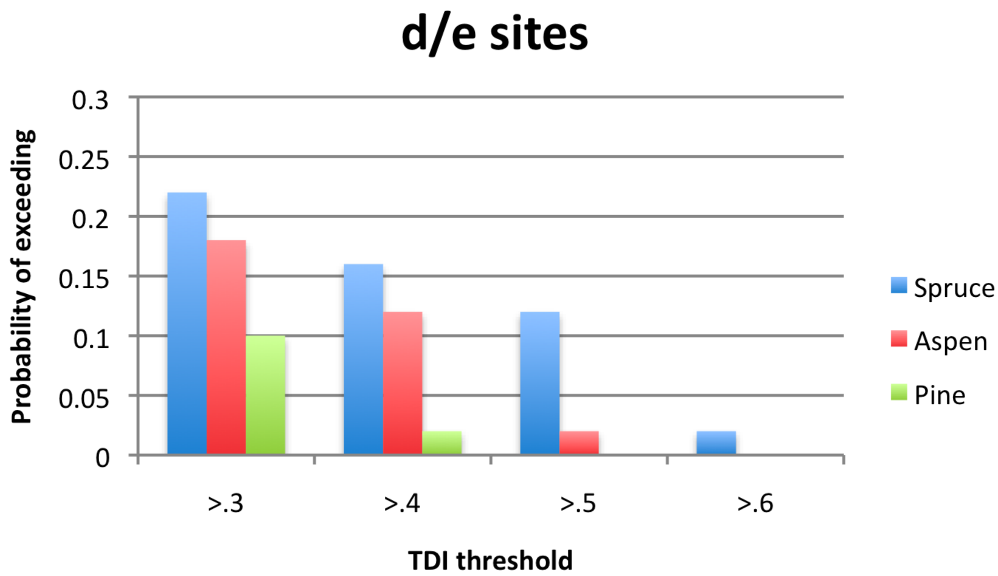


Figure 20. The probability of exceeding threshold levels of water stress as indicated by transpiration deficit index (TDI) for each species planted in a d-e ecosite type.

Among the three species, spruce was the most likely to experience TDI levels greater than 0.3. It was also the only species to reach TDI levels greater than 0.6 during the 25-year simulation period. Jack pine, in contrast, was the least likely to experience high TDI levels and did not exceed levels of 0.5 during any year. The greater vulnerability in spruce is related to a high leaf area index (LAI; and thus a high evaporative surface), only a moderate level of canopy resistance to transpirational moisture loss), and a relatively high permanent wilting point (see Tables 19 and 20). Aspen has a lower canopy resistance than spruce but this is offset by a lower LAI and lower permanent wilting point. The lower permanent wilting point means that aspen can access soil water in relatively drier soils than spruce. Jack pine, a species adapted to dry sites, has the highest canopy resistance, and the lowest permanent wilting among the three species.

It should be noted that, in general, the highest TDI values occurred in the second year of consecutive dry years. Hence, inter-year patterns in precipitation have a disproportionately greater effect on available moisture versus any single year.

The probability of exceeding TDI thresholds was consistently greater in the a-b ecosites relative to the d-e group, though the differences were relatively small. The difference between the ecosite groups was primarily a function of the properties of the mineral soil. The a-b site had greater sand content and lower clay content relative to the d-e site (Table 19), which translates into differences in the capacity to store plant available soil water and drainage rates. The effect of these properties on TDI would have been much greater if not for the 50 cm peat:mineral layer that is applied to each reclaimed site. The water holding capacity of this layer accounts for 70 to 80% of the total water holding capacity of the soil profile (assuming an effective total rooting depth of 85 cm). Other factors that could lead to greater differences between the ecosite groups include radiation load, as affected by slope and aspect, and the effect of slope position on seepage. These factors were not included at this stage of the analysis to elucidate the effect of soil texture alone on soil water storage capacity and drainage rates on reclaimed sites. They will, however, receive consideration during the second phase of the project.

The probabilities reported here are based on the simulated response of the tree-soil combinations to the past 25 years of climate data (1982 to 2006). These years reflect the current climate but are not likely to be representative of future climates. A regional climate change analysis using global climate model (GCM) output for Alberta (Barrow and Yu 2005) projects a substantial and continual decreases in growing season precipitation in the Fort McMurray region over the next 10 to 70 years. These projected decreases combined with warmer temperatures will most likely lead to increases in the frequency of high water stress years. An exploration of the impact of climate change on water stress and its implications for overall growth and the associated development of structural habitat elements will be explored in Phase II of the research.

5 NEXT STEPS

The principal objective in Phase II is an evaluation of the impact of climate and climate change on reclamation success, as compared to the basecase analysis (no climate-related impacts) conducted in Phase I. As in Phase I, the Kearl Lake mine development plan will be used as the test case.

Activities in Phase II will comprise five parts. The basic approach is to explore climate impacts on key components of the reclamation 'cycle'. The potential effect of different climate change scenarios on growth and mortality in reclamation areas will be projected using FORECAST Climate and associated modeling tools to evaluate their combined impacts on overall ecosystem development in a risk assessment context. Stand-level output from FORECAST Climate will then be used to support a spatial analysis of indices of habitat suitability for the Kearl Lake mine development plan. Finally, a detailed, 3-dimensional visual representation of the temporal and spatial development of plantations within a subsection of Kearl Lake mine reclamation area will be created using a spatially explicit modeling tool built to work with FORECAST output.

Phase III activities are focused on a regional-level analysis covering the Lower Athabasca regional planning unit. For practical purposes, this will entail a shift to a more coarse-scale analysis than was conducted in the first two Phases. Nevertheless, much of the protocol and methodology employed in these phases will be applied during Phase III. Significant tasks during Phase III are the application of a modeling platform that can provide a spatial representation of disturbance (fire, logging, seismic exploration, well pads) and the creation of a series of stand-level metrics (using FORECAST) that relate to measures of productivity and wildlife habitat. At this point, the modeling platform has not been selected. Patterns of disturbance will be derived from logging and exploration development plans, while fire disturbance will be simulated using a model that accounts for climate and fuel condition. An analysis of risk will be derived from projected patterns of development in conjunction with wildfire events superimposed on the regional landscape. The latter represent unplanned disturbance and climate change is likely to have a significant impact upon natural fire regimes. This is likely to have a significant impact upon landscape processes and features.

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7 GLOSSARY OF ACRONYMS IN THIS REPORT

AENV	Alberta Environment
AET	Actual Evapotranspiration
EIA	Environmental Impact Assessment
ForWaDy	Forest Water Dynamics (a model)
GHG	Greenhouse Gas
HS	Hybrid Simulation
HSI	Habitat Suitability Index
HU	Habitat Units
LAI	Leaf Area Index
m.a.s.l.	Metres Above Sea Level
NOAA	National Oceanic and Atmospheric Administration
OSEM	Oil Sands Environmental Management Division (in AENV)
OSRIN	Oil Sands Research and Information Network
PET	Potential Evapotranspiration
TDI	Transpiration Deficit Index

ZOI	Zone of Influence

APPENDIX 1: Additional Statistical Data

In this appendix the reader can find the extended statistical data for the correlation and regressions carried out to study possible relationships between tree ring width series and climatic data (Tables A1-1 to A1-5).

Table A1-1. Significant correlations between climate variables and tree ring residual chronologies for white spruce.

Chronology	Variable	Correlation	n	Signif	Plot Correlation (limits -1 to +1)
129	P Jun-Aug <180	0.5669	14	0.0345	
130	P May-Sep	0.4304	22	0.0456	
	P Jun-Aug	0.5013	22	0.0175	
	P May-Sep <330	0.4304	22	0.0456	
	P May-Sep <350	0.4304	22	0.0456	
	P Jun-Aug <180	0.5700	14	0.0333	
	P Jun-Aug <250	0.5013	22	0.0175	
131	P May-Sep	0.5028	22	0.0171	
	P May-Sep <290	0.5677	19	0.0112	
	P May-Sep <330	0.5028	22	0.0171	
	P May-Sep <350	0.5028	22	0.0171	
	P Jun-Aug <220	0.4440	20	0.0499	
145	P Jun-Aug <180	0.6613	12	0.0192	
	PP May-Sep <590	0.5702	20	0.0087	
	PP May-Sep <660	0.5475	27	0.0031	
197	PP May-Sep	0.4342	28	0.0210	
	PP Jun-Aug	0.5482	28	0.0025	
198	P GDD >5 May-Sep	-0.2320	72	0.0499	
	P GDD>5 Jun-Aug	-0.2344	72	0.0475	
	P GDD>10 May-Sep	-0.2393	71	0.0444	
	PP Jun-Aug	0.2513	71	0.0345	
	PP May-Sep <660	0.2885	51	0.0401	
202	PP May-Sep	0.4727	37	0.0031	
	PP Jun-Aug	0.3789	35	0.0248	
	PP May-Sep <660	0.4526	27	0.0178	
205	P May-Sep <330	0.4646	28	0.0127	
	P May-Sep <350	0.4225	32	0.0160	
	PP May-Sep	0.4947	37	0.0019	
	PP Jun-Aug	0.5398	35	0.0008	

Chronology	Variable	Correlation	n	Signif	Plot Correlation (limits -1 to +1)
	PP May-Sep <590	0.4949	20	0.0265	
206	P Jun-Aug <180	0.5833	12	0.0465	
	PP May-Sep	0.5680	37	0.0002	
	PP Jun-Aug	0.4973	35	0.0024	
	PP May-Sep <660	0.5139	27	0.0061	
212	P May-Sep	0.4872	33	0.0040	
	P Jun-Aug	0.3918	33	0.0241	
	P May-Sep <290	0.4454	27	0.0199	
	P May-Sep <330	0.4823	32	0.0052	
	P May-Sep <350	0.4823	32	0.0052	
	P Jun-Aug <220	0.4320	30	0.0171	
	P Jun-Aug <250	0.3918	33	0.0241	
	PP May-Sep	0.4081	33	0.0184	
	PP Jun-Aug	0.3670	33	0.0356	
	PP May-Sep <590	0.4249	31	0.0172	
	PP May-Sep <660	0.3840	32	0.0300	
	PP Jun-Aug <400	0.3820	28	0.0448	
	PP Jun-Aug <450	0.3670	33	0.0356	
213	P May-Sep	0.5124	33	0.0023	
	P Jun-Aug	0.3630	33	0.0379	
	P May-Sep <290	0.4965	27	0.0084	
	P May-Sep <330	0.5012	32	0.0035	
	P May-Sep <350	0.5012	32	0.0035	
	P Jun-Aug <220	0.4119	30	0.0237	
	P Jun-Aug <250	0.3630	33	0.0379	
214	P May-Sep	0.5470	33	0.0010	
	P Jun-Aug	0.3950	33	0.0229	
	P May-Sep <290	0.4524	27	0.0178	
	P May-Sep <330	0.4947	32	0.0040	
	P May-Sep <350	0.4947	32	0.0040	
	P Jun-Aug <220	0.3866	30	0.0348	
	P Jun-Aug <250	0.3950	33	0.0229	
	PP May-Sep	0.3669	33	0.0357	
215	P May-Sep	0.3704	33	0.0339	
	P Jun-Aug	0.3486	33	0.0468	

Chronology	Variable	Correlation	n	Signif	Plot Correlation (limits -1 to +1)
	P May-Sep <330	0.3640	32	0.0406	
	P May-Sep <350	0.3640	32	0.0406	
	P Jun-Aug <250	0.3486	33	0.0468	
216	P May-Sep	0.3816	33	0.0284	
	P May-Sep <290	0.4343	27	0.0236	
	P May-Sep <330	0.4468	32	0.0104	
	P May-Sep <350	0.4468	32	0.0104	
	PP May-Sep <590	0.3757	31	0.0372	
217	P May-Sep	0.4379	33	0.0108	
	P May-Sep <330	0.3663	32	0.0392	
	P May-Sep <350	0.3663	32	0.0392	
218	P May-Sep	0.3464	33	0.0483	
	P May-Sep <290	0.4206	27	0.0289	
	P May-Sep <330	0.3844	32	0.0299	
	P May-Sep <350	0.3844	32	0.0299	
219	P May-Sep	0.4685	33	0.0060	
	P Jun-Aug	0.4194	33	0.0151	
	P May-Sep <290	0.4542	27	0.0173	
	P May-Sep <330	0.4219	32	0.0162	
	P May-Sep <350	0.4219	32	0.0162	
	P Jun-Aug <250	0.4194	33	0.0151	
	PP May-Sep	0.3479	33	0.0472	

All variables had also significant regressions.

Table A1-2. Significant correlations between climate variables and tree ring residual chronologies for jack pine.

Chronology	Variable	Correlation	n	Signif	Plot Correlation (limits -1 to +1)
133	P May-Sep <290	0.5440	21	0.0108	
201	P May-Sep <290	-0.4929	17	0.0444	
203	P Jun-Aug <180	-0.6961	11	0.0174	

All variables also had significant regressions.

Table A1-3. Significant correlations between climate variables and tree ring residual chronologies for black spruce.

Chronology	Variable	Correlation	n	Signif.	Plot Correlation (limits -1 to +1)
Boreas 3	P May-Sep <290	0.5131	18	0.0294	
	P May-Sep <330	0.5590	34	0.0006	
	P May-Sep <350	0.3939	37	0.0158	
	P Jun-Aug <180	0.5784	13	0.0384	
	P Jun-Aug <220	0.5739	27	0.0017	
	P Jun-Aug <250	0.4163	34	0.0143	
	PP May-Sep <590	0.4104	27	0.0335	
	PP May-Sep <660	0.4362	35	0.0088	
	PP Jun-Aug <400	0.6383	17	0.0058	
	PP Jun-Aug <450	0.3634	33	0.0376	

All variables also had significant regressions.

Table A1-4. Significant correlations between climate variables and tree ring residual chronologies for the composite of Alberta's white spruce chronologies.

Chronology	Variable	Correlation	n	Signif.	Plot Correlation (limits -1 to +1)
Alberta	GDD >5 May-Sep	0.0232	33	0.8982	
	GDD >5 Jun-Aug	0.1365	33	0.4487	
	P GDD >5 May-Sep	-0.1660	33	0.3558	
	P GDD>5 Jun-Aug	-0.1095	33	0.5442	
	GDD>10 May-sep	0.1294	33	0.4729	
	GDD>10 Jun-Aug	0.1365	33	0.4487	
	P GDD>10 May-Sep	0.0125	32	0.9459	
	P GDD>10 Jun-Aug	-0.0062	32	0.9730	
	P May-Sep	0.5454	33	0.0010	
	P Jun-Aug	0.4129	33	0.0169	
	P May-Sep <290	0.5201	27	0.0054	
	P May-Sep <330	0.5320	32	0.0017	
	P May-Sep <350	0.5320	32	0.0017	
	P Jun-Aug <180	0.2632	21	0.2489	
	P Jun-Aug <220	0.3973	30	0.0297	
	P Jun-Aug <250	0.4129	33	0.0169	
	PP May-Sep	0.3779	33	0.0302	

Chronology	Variable	Correlation	n	Signif.	Plot Correlation (limits -1 to +1)
	PP Jun-Aug	0.3576	33	0.0410	
	PP May-Sep <520	0.3006	25	0.1443	
	PP May-Sep <590	0.3809	31	0.0345	
	PP May-Sep <660	0.3334	32	0.0622	
	PP Jun-Aug <350	0.3473	21	0.1230	
	PP Jun-Aug <400	0.3375	28	0.0790	
	PP Jun-Aug <450	0.3576	33	0.0410	

All variables also had significant regressions.

Table A1-5. Significant correlations between climate variables and tree ring residual chronologies for the composite of Alberta's jack pine chronologies.

Chronology	Variable	Correlation	n	Signif.	Plot Correlation (limits -1 to +1)
Alberta	GDD >5 May-Sep	0.0219	25	0.9171	
	GDD >5 Jun-Aug	0.0160	25	0.9396	
	P GDD >5 May-Sep	-0.1433	25	0.4945	
	P GDD>5 Jun-Aug	-0.1883	25	0.3674	
	GDD>10 May-sep	-0.0010	25	0.9962	
	GDD>10 Jun-Aug	0.0160	25	0.9396	
	P GDD>10 May-Sep	-0.1607	24	0.4531	
	P GDD>10 Jun-Aug	-0.1739	24	0.4165	
	P May-Sep	0.2481	25	0.2318	
	P Jun-Aug	0.3932	25	0.0519	
	P May-Sep <290	0.5200	21	0.0157	
	P May-Sep <330	0.2481	25	0.2318	
	P May-Sep <350	0.2481	25	0.2318	
	P Jun-Aug <180	0.4035	15	0.1358	
	P Jun-Aug <220	0.3261	23	0.1289	
	P Jun-Aug <250	0.3932	25	0.0519	
	PP May-Sep	0.0856	25	0.6843	
	PP Jun-Aug	0.2064	25	0.3222	
	PP May-Sep <520	0.1944	20	0.4115	
	PP May-Sep <590	0.0856	25	0.6843	
	PP May-Sep <660	0.0856	25	0.6843	
	PP Jun-Aug <350	0.0642	16	0.8133	

Chronology	Variable	Correlation	n	Signif.	Plot Correlation (limits -1 to +1)
	PP Jun-Aug <400	0.2323	21	0.3110	
	PP Jun-Aug <450	0.2064	25	0.3222	

All variables also had significant regressions.

APPENDIX 2: Habitat Suitability Models

Moose (*Alces alces*)

The habitat suitability model for moose takes into account food and cover components, and also the interspersion of habitat suitable for any of those purposes and the zone of influence of disturbances. The model is formulated as:

$$HSI_{food} = SI_{Preferred\ Browse}$$

$$HSI_{cover} = \sqrt[3]{SI_{SconiferCC} \text{ x } SI_{CH} \text{ x } SI_{CC}}$$

$$HSI_{MOOSE} = \sqrt{(Max(HSI_{food} \quad HSI_{cover}) \times SI_{HI})}$$ (no disturbance effect included)

To account for the effect of disturbances, the final HSI is HSI_{MOOSE} x $SI_{ZOI\ Disturbance\ Coeff}$; these coefficients will be included in the Phase II habitat suitability analysis.

The variables for the model are calculated as follows:

Preferred browse canopy cover ($S_{browse}CC$). These include birch, poplar and aspen. Additional species are willow, red osier dogwood, saskatoon, low-bush cranberry, buffaloberry chokecherry and pincherry. The relationship with SI is:

If $S_{browse}CC \leq 50\%$ $SI_{preferred\ browse} = 3.1791\ S_{browse}CC - 2.5793\ (S_{browse}CC)^2$

If $S_{browse}CC > 50\%$ $SI_{preferred\ browse} = 1$

Conifer canopy closure ($S_{conifer}CC$). The relationship with SI is:

If $S_{conifer}CC \leq 60\%$ $SI_{SconiferCC} = 0.2 + 1.4263\ S_{conifer}CC - 0.2512\ (S_{conifer}CC)^2$

If $S_{conifer}CC > 60\%$ $SI_{SconiferCC} = 1$

Canopy height (CH in meters). The relationship with SI is:

If $CH \leq 15m$ $SI_{CH} = 0.1038\ CH - 0.0027\ CH^2$

If $CH > 15m$ $SI_{CH} = 1$

Tree canopy closure (CC). The relationship with SI is:

If $CC \leq 70\%$ $SI_{CC} = 0.2 + 0.887\ CC + 0.2891CC^2$

If $CC > 70\%$ $SI_{CC} = 1$

Habitat interspersion (HI). This variable takes into account how much of the habitat in the area can be considered as habitat for food and how much can be considered as habitat for cover. The proportions of each type of habitat (P_{food} and $P_{cover,}$) are values from 0 to 1 that summed together equal 1. The ideal proportion is 30% habitat for cover and 70% habitat for food. For other combinations, their relationship with SI is:

$$SI_{HI} = 0.8696\, e^{-0.5\cdot\left(\left(\frac{P_{food}-0.7279}{0.4773}\right)^2+\left(\frac{P_{cover}-0.3102}{0.3904}\right)^2\right)}$$

In order to simplify the analysis, the calculations presented in this report assume that the habitat interspersion is in its ideal proportion. In addition, no ZOI were taken into account, which is equivalent to assume that there was not reduction of habitat by human activities. As a result, the HSI for moose can be considered as determined under “optimal” conditions, and actual values will likely be lower than calculated here.

Black bear (*Ursus americanus*)

The habitat suitability model for black bear takes into account the food and cover components, and also the interspersion of habitat suitable for any of those purposes and the zone of influence of disturbances. The model is formulated as:

$HSI_{food} = SI_{Berries}$

$$HSI_{cover} = Max\left[SI_{SC}, \left(\sqrt{SI_{CC} \times S_{ST}}\right)\right]$$

$$HSI_{BLACK\ BEAR} = \sqrt{(Max(HSI_{food}, HSI_{cover}) \times SI_{HI})}$$ (no disturbance effect included)

To account for the effect of disturbances, the final HSI is $HSI_{overall}$ x $SI_{ZOI\ Disturbance\ Coeff.}$ The disturbance coefficients for black bear are 0.75 for any site less than 500 m from any active road, railway, airstrip, urban, residential and industrial sites.

The variables for the model are calculated as follows:

Berry producers ($S_{berries}CC$). Species considered important berry producers include buffalo-berry, blueberry, Saskatoon, low-bush cranberry, rose, currant, raspberry, bearberry, bog cranberry and crowberry. The relationship with SI is:

If $S_{berries}CC \leq 50\%$ $SI_{berries} = 0.2 + 1.5985\ S_{berries}CC$

If $S_{berries}CC > 50\%$ $SI_{berries} = 1$

Shrub canopy closure (SC). The relationship with SI is:

$SI_{SC} = 1.9193\ SC - 1.0634\ SC^2$

Tree canopy closure (CC). The relationship with SI is:

If $CC \leq 70\%$ $SI_{CC} = 0.2 + 0.6089\ CC + 0.7172\ CC^2$

If $CC > 70\%$ $SI_{CC} = 1$

Structural Stage (ST). The relationship with SI is given in Table A2-1.

TableA2-1. Suitability index multipliers for black bear in relationships to tree maturity and structural stage.

Structural Stage	SI_{ST}
Non-vegetated	0.0
Herbaceous	0.0
Low shrub	0.1
Tall shrub	0.2
Pole sapling	0.5
Young forest	1.0
Mature forest	1.0
Old-growth forest	1.0

Habitat interspersion (HI). This variable takes into account how much of the habitat in the area can be considered as habitat for food and how much can be considered as habitat for cover. The proportions of each type of habitat (P_{food} and $P_{cover,}$) are values from 0 to 1 that together sum 1. The ideal proportion is 30% habitat for cover and 70% habitat for food. For other combinations, their relationship with SI is:

$$SI_{HI} = 0.8696\, e^{-0.5 \cdot \left(\left(\frac{P_{food} - 0.7279}{0.4773} \right)^2 + \left(\frac{P_{cover} - 0.3102}{0.3904} \right)^2 \right)}$$

In order to simplify the analysis, the calculations presented in this report assume that the habitat interspersion is in its ideal proportion. In addition, no ZOI were taken into account, which is equivalent to assume that there was not reduction of habitat by human activities. As a result, the HSI for black bear can be considered as determined under “optimal” conditions, and actual values will likely be lower than calculated here.

Snowshoe hare (*Lepus americanus*)

The habitat suitability model for snowshoe hare takes into account the food and cover components, and also the interspersion of habitat suitable for any of those purposes. The model is formulated as:

$$HSI_{food} = \sqrt[3]{SI_{SC} \times SI_{\text{Preferred Browse}} \times SI_{SH}}$$

$$HSI_{cover} = Max\left[SI_{SC}, \left(\sqrt{SI_{CC} \times SI_{spruce/fir}} \right) \right]$$

$$HSI_{SNOWSHOE\ HARE} = \frac{HSI_{food} + HSI_{cover}}{2}$$

The variables for the model are calculated as follows:

Preferred browse canopy cover ($S_{browse}CC$). These include alder, paper birch and swamp birch, larch and jackpine, and also saskatoon hazelnut, rose, raspberry, willows and buffalo-berry. The relationship with SI is:

If $S_{browse}CC \leq 50\%$ $SI_{preferred\ browse} = 0.4 + 1.2376\ S_{browse}CC$

If $S_{browse}CC > 50\%$ $SI_{preferred\ browse} = 1$

Shrub cover (SC). The relationship with SI is:

If $SC \leq 90\%$ $SI_{SC} = 1.0918\ SC$

If $SC > 90\%$ $SI_{SC} = 1$

Shrub height (SH in meters). The relationship with SI is:

If $CH \leq 1.5m$ $SI_{SH} = 0.5 + 1.7084\ SH - 1.3148\ SH^2$

If $CH > 1.5m$ $SI_{SH} = 0$

Tree canopy closure (CC). The relationship with SI is:

If $CC \leq 50\%$ $SI_{CC} = 0.4 + 0.2735\ CC + 1.7823\ CC^2$

If $CC > 50\%$ $SI_{CC} = 1$

Spruce or fir canopy closure ($S_{spruce\ fir}\ CC$). The relationship with SI is:

If $S_{spruce\ fir}\ CC \leq 50\%$ $SI_{Spruce\ fir} = 0.733\ S_{spruce\ fir}\ CC + 2.4576\ (S_{spruce\ fir}\ CC)^2$

If $S_{spruce\ fir}\ CC > 50\%$ $SI_{Spruce\ fir} = 1$

Lynx (*Lynx canadensis*)

The habitat suitability model for lynx takes into account the food and cover components, and also the interspersion of habitat suitable for any of those purposes. The model for lynx is formulated as:

$HSI_{food} = HIS_{Snowshoe\ hare}$

$$HSI_{cover} = \sqrt{SI_{CC} \times SI_{SC}}$$

$$HSI_{LYNX} = 0.8 \times HSI_{food} + 0.2 \times HSI_{cover}$$ (no disturbance effect included)

The variables for the model are calculated as follows:

Tree canopy closure (CC). The relationship with SI is:

If $CC \leq 70\%$ $SI_{CC} = 0.1 + 0.5311\ CC + 1.1181\ CC^2$

If CC > 70% $SI_{CC} = 1$

Shrub cover (SC). The relationship with SI is:

If SC ≤ 70% $SI_{SC} = 2.9573\ SC - 2.3116\ SC^2$

If SC > 70% $SI_{SC} = 1$

In order to simplify the analysis, no ZOI were taken into account, which is equivalent to assuming that there was no reduction in habitat suitability by human activities. As a result, the HSI for lynx can be considered as calculated under "optimal" conditions, and actual values may be lower.

Red-backed vole (*Myodes rutilus*)

The habitat suitability model for red-backed vole is simple and only takes into account a combined measure of both food and cover components. The model is formulated as:

$$HSI_{RED-BACKED\ \ VOLE} = \sqrt[3]{SI_{ST} \times SI_{CC} \times SI_{SC}}$$

The variables for the model are calculated as follows:

Structural Stage (ST). The relationship with SI is given in Table A2-2.

TableA2-2. Suitability index multipliers for red-backed vole in relationships to tree maturity and structural stage.

Structural Stage	SI_{ST}
Non-vegetated	0.00
Herbaceous	0.05
Low shrub	0.05
Tall shrub	0.05
Pole sapling	0.15
Young forest	0.65
Mature forest	1.00
Old-growth forest	1.00

Tree canopy closure (CC). The relationship with SI is:

If CC ≤ 70% $SI_{CC} = 1.8168\ CC$

If CC > 70% $SI_{CC} = 1$

Shrub cover (SC). The relationship with SI is:

If SC ≤ 70% $SI_{SC} = 0.2 + 1.1572\ SC$

If SC > 70% $SI_{SC} = 1$

Fisher (*Martes pennanti*)

The habitat suitability model for fisher takes into account the food and cover components, and also the interspersion of habitat suitable for any of those purposes and the zone of influence of disturbances. Given the strong dependence of fisher on small mammals such as snowshoe hares or red-backed voles as main food source, the models for snowshoe hare and red-backed vole have to be calculated first. The model for fisher is formulated as:

$$HSI_{food} = Max\left(HSI_{Snowshoe\ hare}, HSI_{red\text{-}backed\ vole}\right)$$

$$HSI_{cover} = \sqrt[3]{SI_{CC} \times SI_{conifer} \times SI_{ST}}$$

$$HSI_{FISHER} = \sqrt{Max\left(HSI_{food}, HSI_{cover}\right) \times SI_{interspersion}}$$

The variables for the model are calculated as follows:

Tree canopy closure (CC). The relationship with SI is:

If CC ≤ 70% $SI_{CC} = 0.7075\ CC + 0.9923\ CC^2$

If CC > 70% $SI_{CC} = 1$

Conifer canopy closure ($S_{conifer}CC$). The relationship with SI is:

If $S_{conifer}CC \leq 70\%$ $SI_{conifer} = 0.1 + 3.4435\ S_{conifer}CC - 3.3647\ (S_{conifer}CC)^2$

If $S_{conifer}CC > 70\%$ $SI_{conifer} = 0.8$

Structural Stage (ST). The relationship with SI is given in Table A2-3.

Table A2-3. Suitability index multipliers for fisher in relationships to tree maturity and structural stage.

Structural Stage	**SI_{ST}**
Non-vegetated	0.0
Herbaceous	0.0
Low shrub	0.2
Tall shrub	0.3
Pole sapling	0.4
Young forest	0.6
Mature forest	0.9
Old-growth forest	1.0

Habitat interspersion (HI). This variable takes into account how much of the habitat in the area can be considered as habitat for food and how much can be considered as habitat for cover. The proportions of each type of habitat (P_{food} and $P_{cover,}$) are values from 0 to 1 that together sum 1. The ideal proportion is 60% habitat for cover and 40% habitat for food. For other combinations, their relationship with SI is:

$$SI_{HI} = 0.8612\, e^{-0.5\cdot\left(\left(\frac{P_{food}-0.4025}{0.4082}\right)^2+\left(\frac{P_{cover}-0.6087}{0.4548}\right)^2\right)}$$

In order to simplify the analysis, the calculations presented in this report assume that the habitat interspersion is in its ideal proportion. As a result, the HSI for fisher can be considered as calculated under “optimal” conditions, and actual values may be lower.

Cape May Warbler (*Dendroica tigrina*)

The habitat suitability model for Cape May warbler is simple and only takes into account a combined measure of both food and cover components. The model is formulated as:

$$HSI_{CAP\ MAY\ WARBLER} = \sqrt{\sqrt[4]{SI_{ST} \times SI_{CC} \times SI_{conifer} \times SI_{CH}} \times SI_{dominant\ species}}$$

The variables for the model are calculated as follows:

Structural Stage (ST). The relationship with SI is given in Table 3.10.

Table A2-4. Suitability index multipliers for Cap May warbler in relationships to tree maturity and structural stage.

Structural Stage	SI_{ST}
Non-vegetated	0.0
Herbaceous	0.0
Low shrub	0.0
Tall shrub	0.0
Pole sapling	0.1
Young forest	0.5
Mature forest	0.9
Old-growth forest	1.0

Tree canopy closure (CC). The relationship with SI is:

If $CC \leq 70\%$ $SI_{CC} = 4.447\ CC - 5.1009\ CC^2$

If $CC > 70\%$ $SI_{CC} = 0.6$

Conifer Canopy closure ($S_{conifer}CC$). The relationship with SI is:

If $S_{conifer}CC \leq 70\%$ $SI_{conifer} = 0.1 - 0.1385\ S_{conifer}CC + 2.0227\ (S_{conifer}CC)^2$

If $S_{conifer}CC > 70\%$ $SI_{conifer} = 1$

Canopy height (CH). The relationship with SI is:

If CH < 10 m $SI_{CH} = 0.2$

If CH ≥ 10 m and CH ≤ 15 m $SI_{CH} = 0.8$

If CH > 15 m $SI_{CH} = 1$

Dominant overstory species: The relationship with SI is provided in Table A2-5.

Table A2-5. Suitability index multipliers for Cap May warbler in relationships to dominant overstory species

Dominant species	**$SI_{dominant\ species}$**
Deciduous	0.3
Other conifer	0.5
Balsam fir	0.7
White spruce	1.0

Ruffed grouse (*Bonasa umbellus*)

The habitat suitability model for ruffed grouse takes into account the food and cover components, and also the interspersion of habitat suitable for any of those purposes. The model is formulated as:

$$HSI_{food} = \sqrt{Max\left(SI_{SC}, \sqrt{SI_{deciduous} \times SI_{STfood}}\right) \times SI_{preferred\ food}}$$

$$HSI_{cover} = \sqrt{SI_{CC} \times SI_{ST\ cover}}$$

$$HSI_{RUFFED GROUSE} = \sqrt{(Max(HSI_{food}, HSI_{cover}) \times SI_{HI})}$$

The variables for the model are calculated as follows:

Shrub cover (SC). The relationship with SI is:

If SC ≤ 90% $SI_{SC} = 3.1191\ SC - 2.5633\ SC^2$

If SC > 90% $SI_{SC} = 0.7$

Structural Stage food (ST_{food}). The relationship with SI is given in Table A2-6.

Table A2-6. Suitability index multipliers for ruffed grouse food availability in relationships to tree maturity and structural stage.

Structural Stage	**SI_{STfood}**
Non-vegetated	0.0
Herbaceous	0.0
Low shrub	0.0
Tall shrub	0.0
Pole sapling	0.4
Young forest	0.8
Mature forest	1.0
Old-growth forest	1.0

Deciduous canopy closure ($S_{deciduous}CC$). The relationship with SI is:

If $S_{deciduous}CC \leq 80\%$ $SI_{deciduous} = 1.2098\ S_{deciduous}CC$

If $S_{deciduous}CC > 80\%$ $SI_{deciduous} = 1$

Preferred food cover ($S_{preferred\ food}\ CC$). Cover of aspen, willow or berry producers. The relationship with SI is:

If $S_{preferred\ food}CC \leq 50\%$ $SI_{preferred\ food} = 1.8064\ S_{preferred\ food}CC$

If $S_{preferred\ food}CC > 50\%$ $SI_{preferred\ food} = 1$

Tree canopy closure (CC). The relationship with SI is:

If $CC \leq 70\%$ $SI_{CC} = 1.5058\ CC$

If $CC > 70\%$ $SI_{CC} = 1$

Structural Stage cover (ST_{cover}). The relationship with SI is given in Table A2-7.

Table A2-7. Suitability index multipliers for ruffed cover availability in relationships to tree maturity and structural stage.

Structural Stage	**$SI_{STcover}$**
Non-vegetated	0.0
Herbaceous	0.0
Low shrub	0.0
Tall shrub	0.0
Pole sapling	0.9

Structural Stage	$SI_{STcover}$
Young forest	1.0
Mature forest	0.4
Old-growth forest	0.0

Habitat interspersion (HI). This variable takes into account how much of the habitat in the area can be considered as habitat for food and how much can be considered as habitat for cover. The proportions of each type of habitat (P_{food} and $P_{cover,}$) are values from 0 to 1 that together sum 1. The ideal proportion is 50% habitat for cover and 50% habitat for food. For other combinations, their relationship with SI is:

$$SI_{HI} = e^{-0.5\cdot\left(\left(\frac{P_{food}-0.6009}{0.3115}\right)^2+\left(\frac{P_{cover}-0.6009}{0.3115}\right)^2\right)}$$

In order to simplify the analysis, the calculations presented in this report assume that the habitat interspersion is in its ideal proportion. As a result, the HSI for ruffed grouse can be considered as calculated under “optimal” conditions, and actual values may be lower.

Pileated woodpecker (*Dryocopus pileatus*)

The habitat suitability model for pileated woodpecker takes into account the availability of nesting sites and winter food components. The model is formulated as:

$$HSI_{food} = \sqrt{SI_{CC} \times SI}_{ST}$$

$$HSI_{nesting} = \sqrt{SI_{deciduous} \times SI_{ST}}$$

$$HSI_{PILEATED\ \ WOODPECKER} = Min\left(HSI_{food}\ , HSI_{nesting\ in\ 200Ha}\right)$$

Deciduous canopy closure ($S_{deciduous}CC$). The relationship with SI is:

If $S_{deciduous}CC \leq 80\%$ $\quad SI_{deciduous} = 0.4 - 0.0428\ S_{deciduous}CC + 0.934\ S_{deciduous}CC^2$

If $S_{deciduous}CC > 80\%$ $\quad SI_{deciduous} = 1$

Tree canopy closure (CC). The relationship with SI is:

If $CC \leq 5\%$ $\quad SI_{CC} = 0$

If $CC > 5\%$ and $CC \leq 70\%$ $\quad SI_{CC} = 1$

If $CC > 70\%$ $\quad SI_{CC} = 0.8$

Structural stage (ST). The relationship with SI is given in Table A2-8.

Table A2-8. Suitability index multipliers for pileated woodpecker in relationships to tree maturity and structural stage.

Structural Stage	**SI_{ST}**
Non-vegetated	0.0
Herbaceous	0.0
Low shrub	0.0
Tall shrub	0.0
Pole sapling	0.0
Young forest	0.3
Mature forest	0.8
Old-growth forest	1.0

Nesting Habitat Units per 200 ha ($HSI_{nesting}$). This is a spatial-related variable that account for the availability of nesting sites in an area of 200 ha surrounding the site for which the HSI for pileated woodpecker is being calculated. This variable can be ignored, accepting an implicit value of 1, which equals to assuming any given prescription for which the HSI is being calculated always has at least one HU for nesting. If it is not ignored, the relationship with SI is:

If $HSI_{nesting} \leq 1$ $\quad SI_{nesting\ 200\ ha} = 0.455\ HSI_{nesting} + 0.56\ (HSI_{nesting})^2$

If $HSI_{nesting} > 1$ $\quad SI_{nesting\ 200\ ha} = 1$

In order to simplify the analysis, the calculations presented in this report assume that the number of nesting habitat units per 200 ha is at least 1. As a result, the HSI for pileated woodpecker can be considered as calculated under "optimal" conditions, and actual values may be lower.

Northern goshawk (*Accipiter gentilis*)

The habitat suitability model for northern goshawk takes into account the availability of nesting sites, the quality of the area for breeding and the zone of influence of disturbance. The model is formulated as:

$$HSI_{breeding} = \sqrt[4]{SI_{CH} \times SI_{CC} \times SI_{deciduous} \times SI_{ST}}$$

$$HSI_{NORTHERN\ GOSHAWK} = Min\left(HSI_{breeding}, SI_{nesting500ha}\right) \text{ (no disturbance effect included)}$$

The variables for the model are calculated as follows:

Canopy height (CH). The relationship with SI is:

If $CH \leq 20$ m $\quad SI_{CH} = -0.0014\ CH + 0.0025\ CH^2$

If $CH > 20$ m $\quad SI_{CH} = 1$

Tree canopy closure (CC). The relationship with SI is:

If $CC \leq 70\%$ $\quad SI_{CC} = 1.9669\ CC - 0.8017\ CC^2$

If $CC > 70\%$ $\quad SI_{CC} = 1$

Deciduous canopy closure ($S_{deciduous}CC$). The relationship with SI is:

$$SI_{deciduous} = 0.4 + 2.1682\ S_{deciduous}CC – 2.1293\ S_{deciduous}CC^2$$

Structural stage (ST). The relationship with SI is given in Table A2-9.

Table A2-9. Suitability index multipliers for northern goshawk in relationships to tree maturity and structural stage.

Structural Stage	$\mathbf{SI_{ST}}$
Non-vegetated	0.0
Herbaceous	0.0
Low shrub	0.05
Tall shrub	0.05
Pole sapling	0.1
Young forest	0.3
Mature forest	1.0
Old-growth forest	1.0

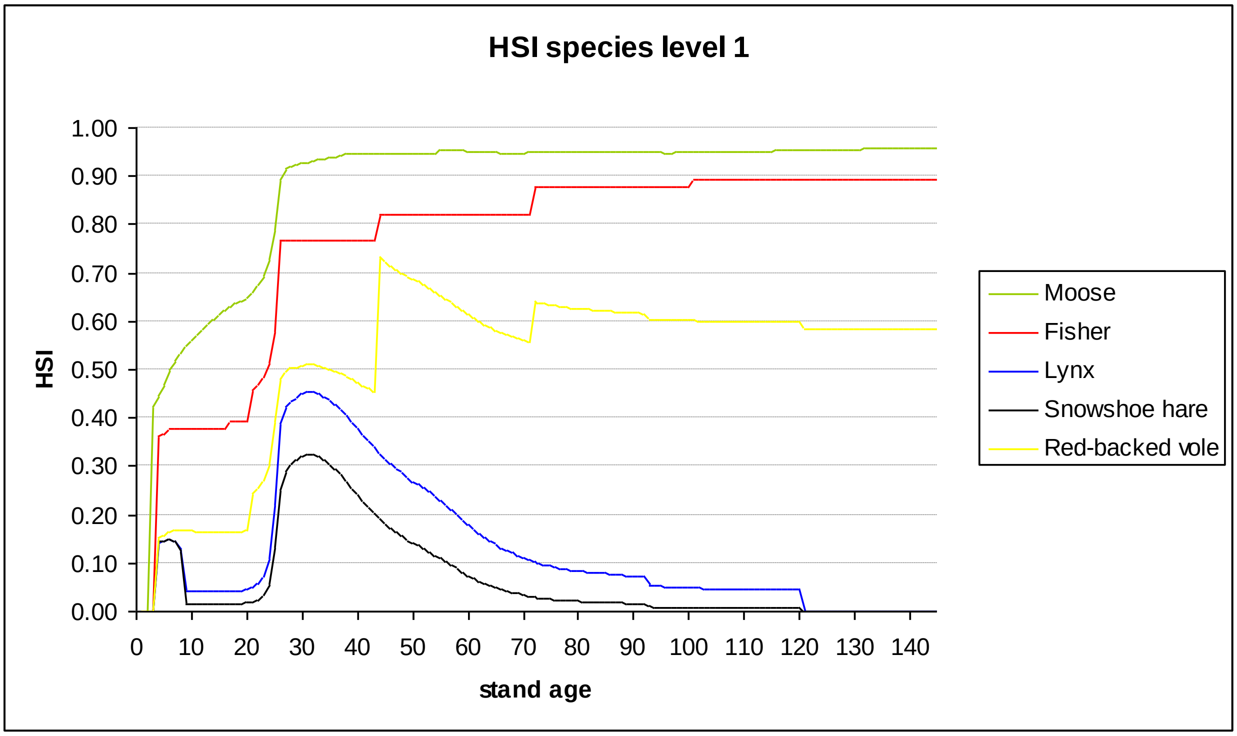
Nesting Habitat Units per 500 ha ($HSI_{nesting}$). This is a spatial-related variable that account for the availability of nesting sites in an area of 500 Ha surrounding the site for which the HSI for northern goshawk is being calculated. This variable can be ignored, accepting an implicit value of 1, which equals to assuming any given prescription for which the HSI is being calculated always has at least one HU for nesting. If it is not ignored, the relationship with SI is:

If $HSI_{nesting} \leq 5$ $\quad SI_{nesting\ 500\ ha} = 0.09\ HSI_{nesting} + 0.022\ (HSI_{nesting})^2$

If $HSI_{nesting} > 5$ $\quad SI_{nesting\ 500\ ha} = 1$

In order to simplify the analysis, the calculations presented in this report assume that the number of nesting habitats units per 500 ha are at least 5. As a result, the HSI for northern goshawk can be considered as calculated under “optimal” conditions, and actual values may be lower.

APPENDIX 3: Habitat Suitability Indices (HSIs) by Ecosite Phase



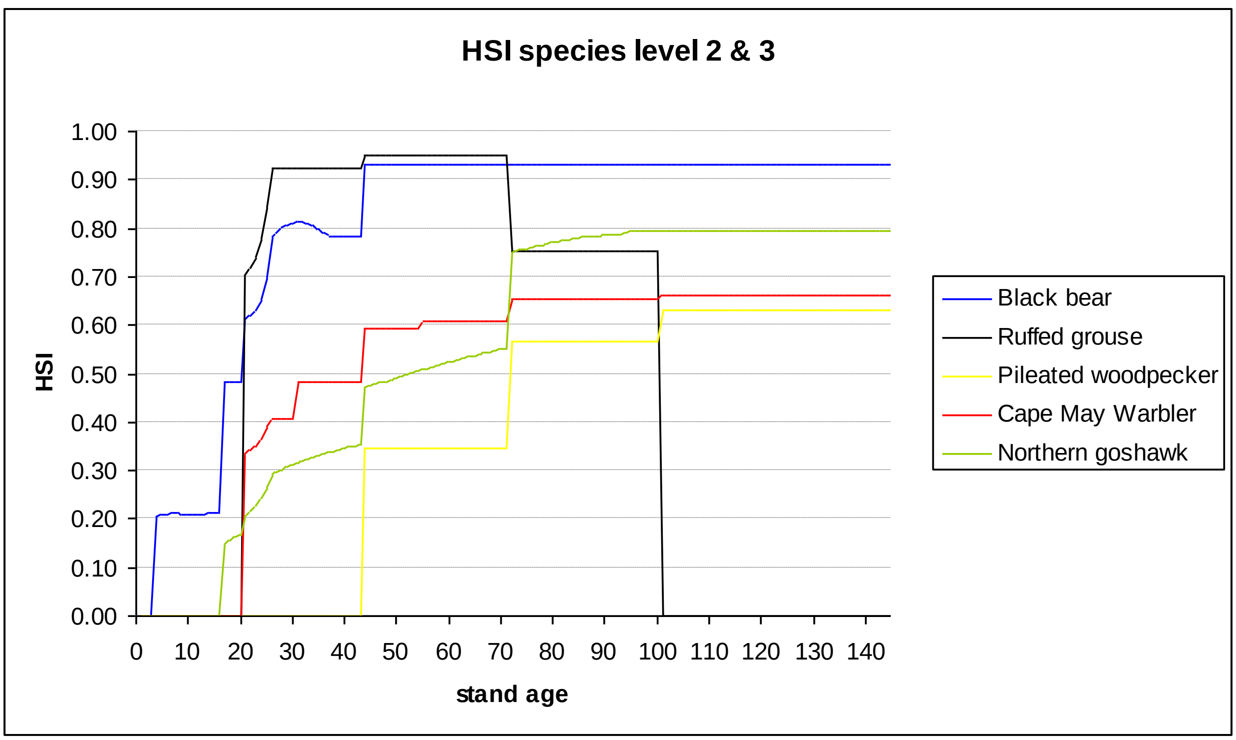
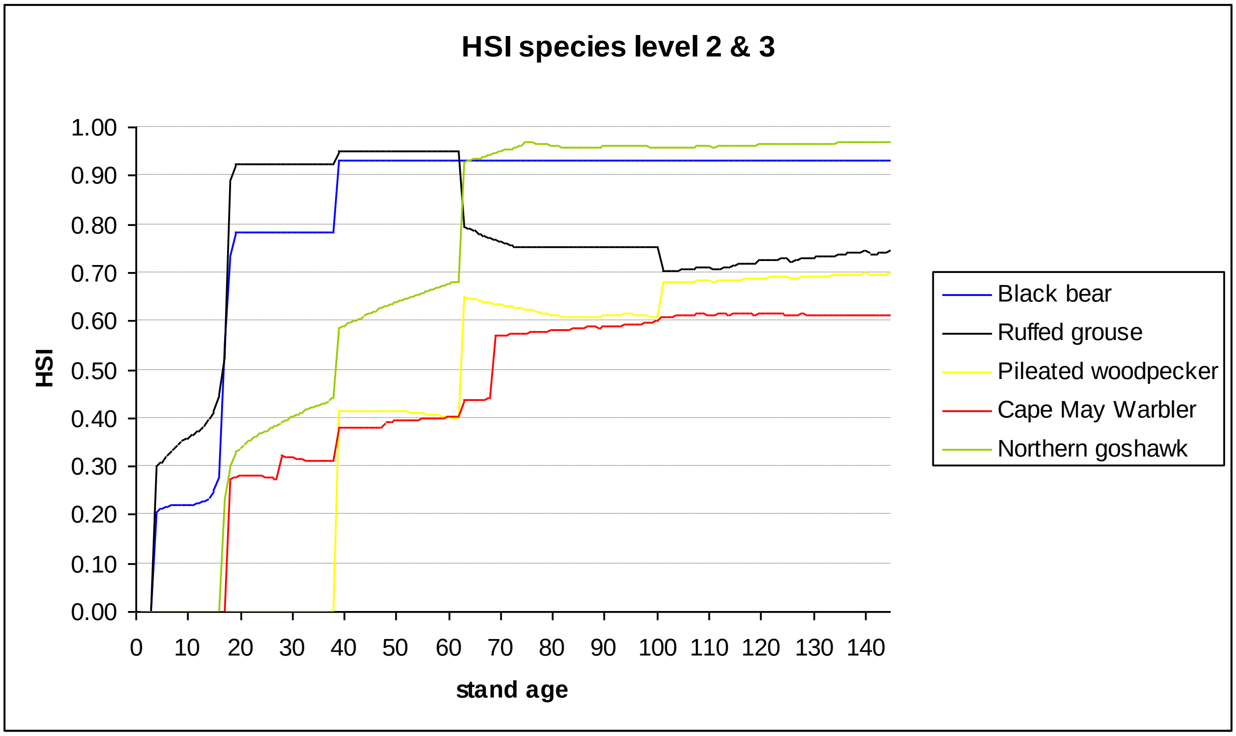


Figure A3-1. HSI values by stand age for ecosite a (= ecosite phase a1).



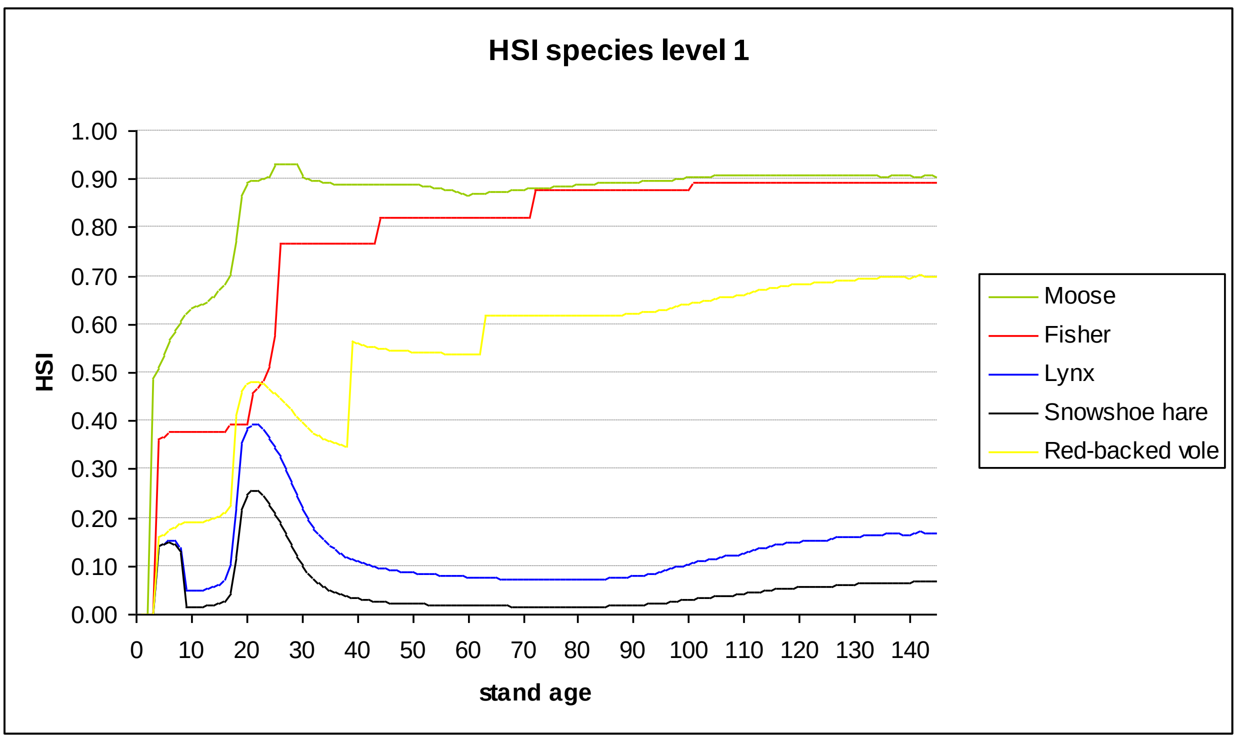
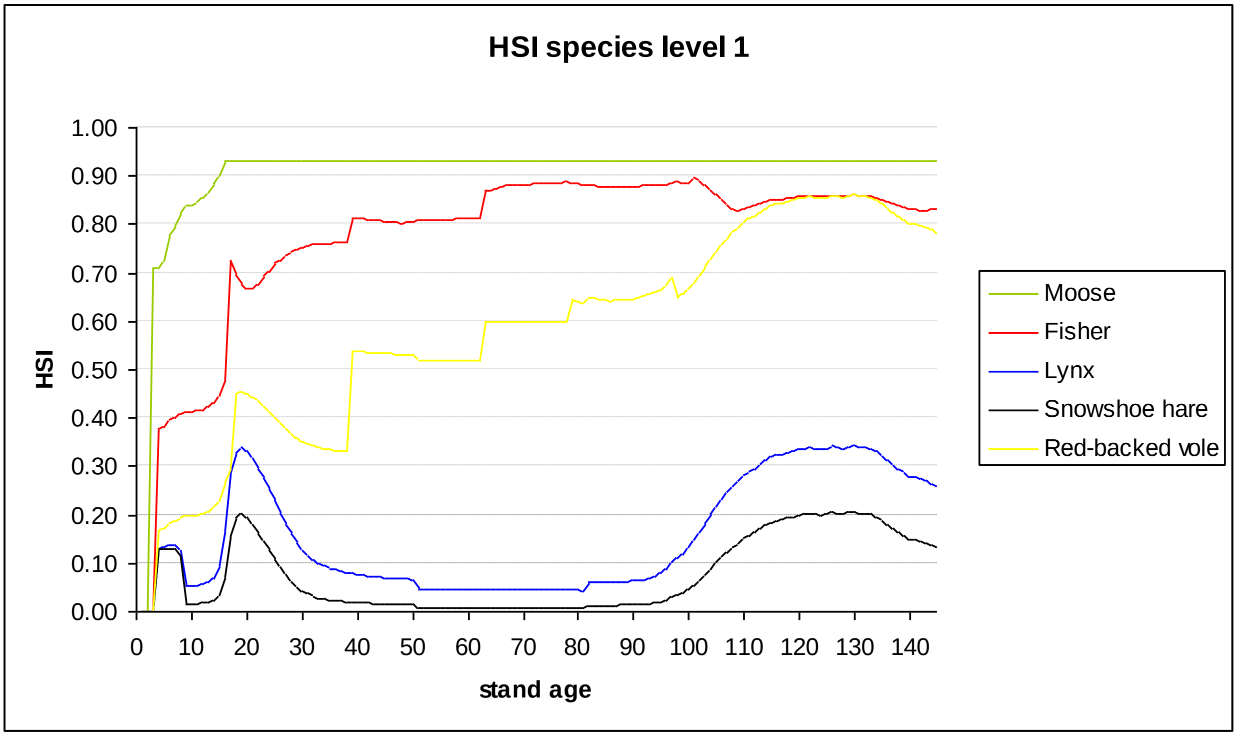


Figure A3-2. HSI values by stand age for ecosite phase b1.



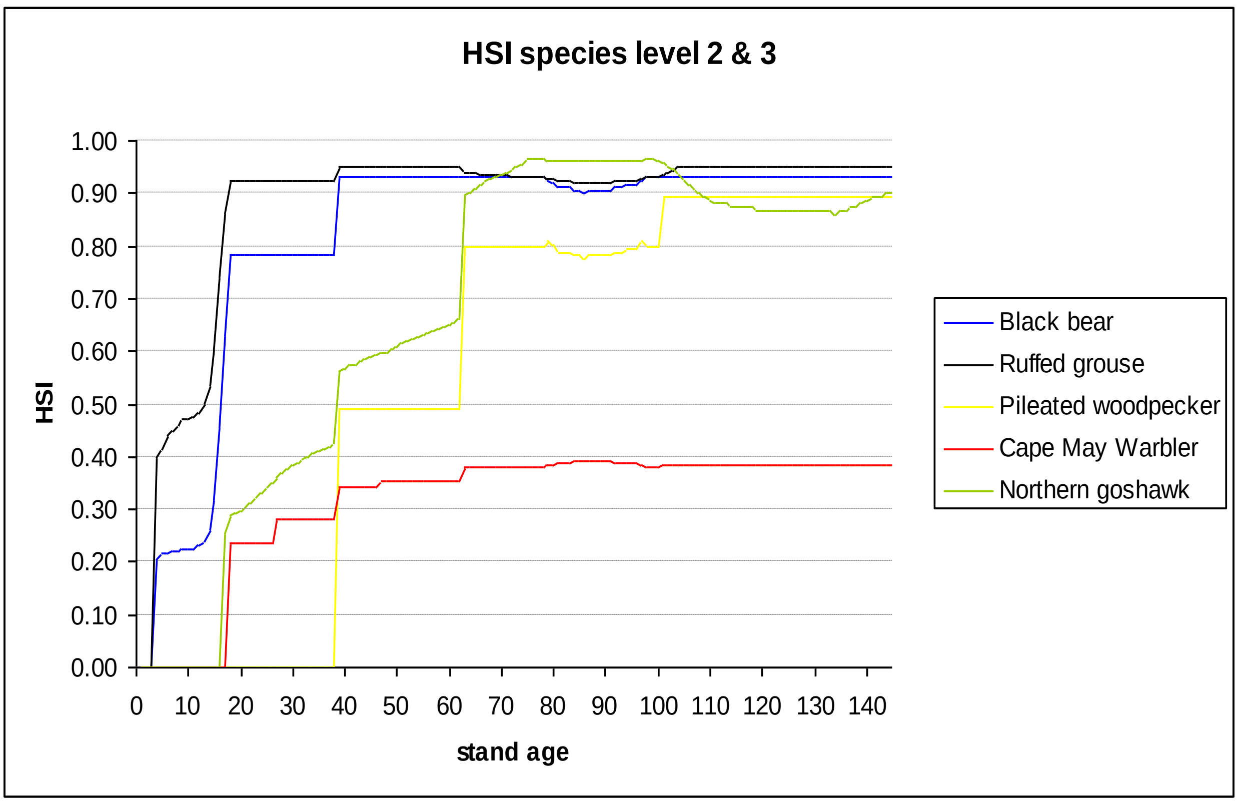


Figure A3-3. HSI values by stand age for ecosite phase b2.

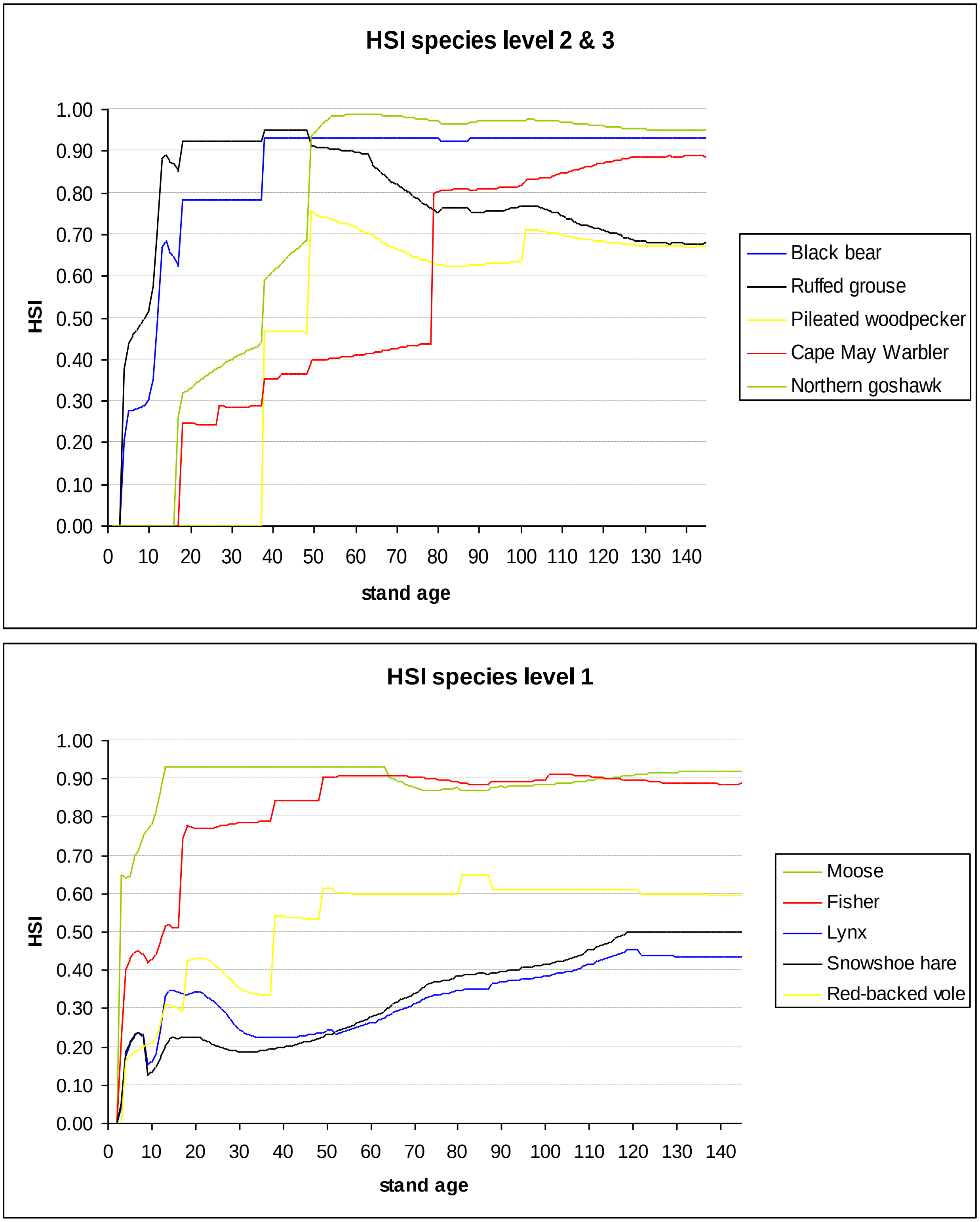
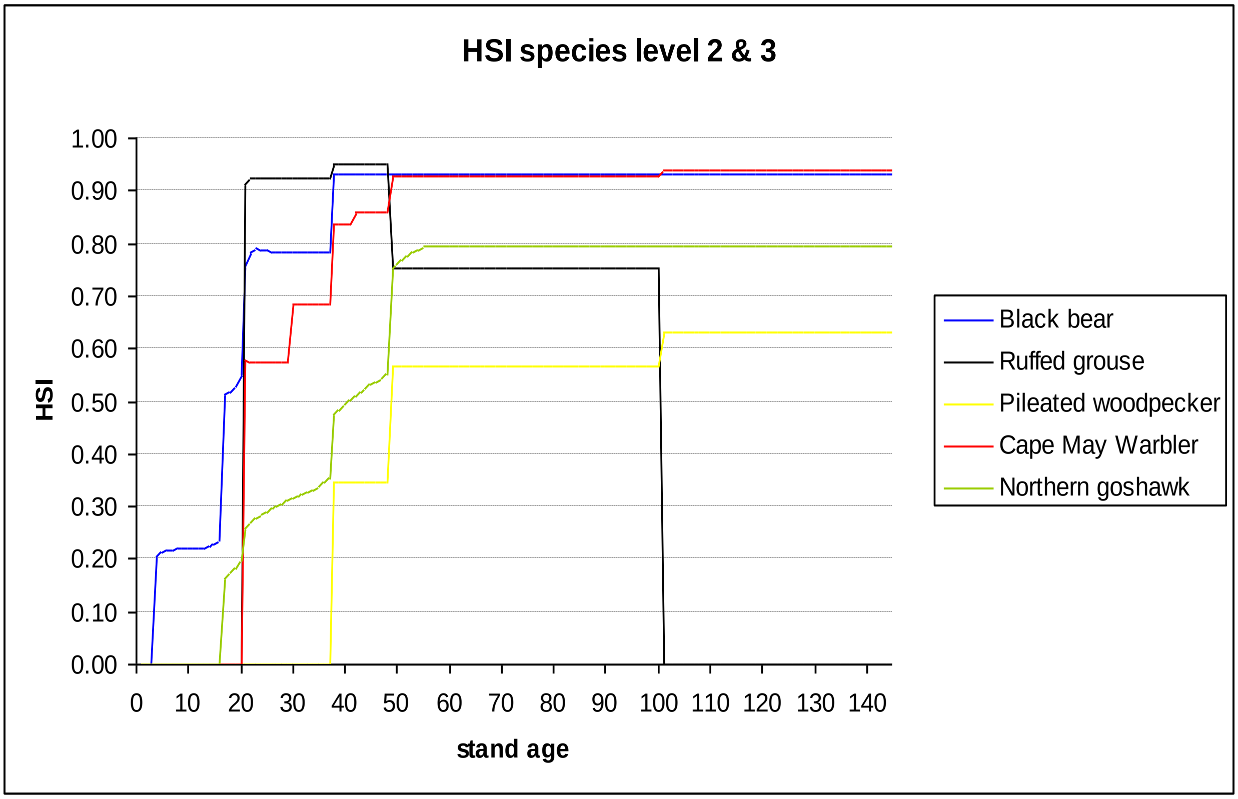


Figure A3-4. HSI values by stand age for ecosite phase b3.



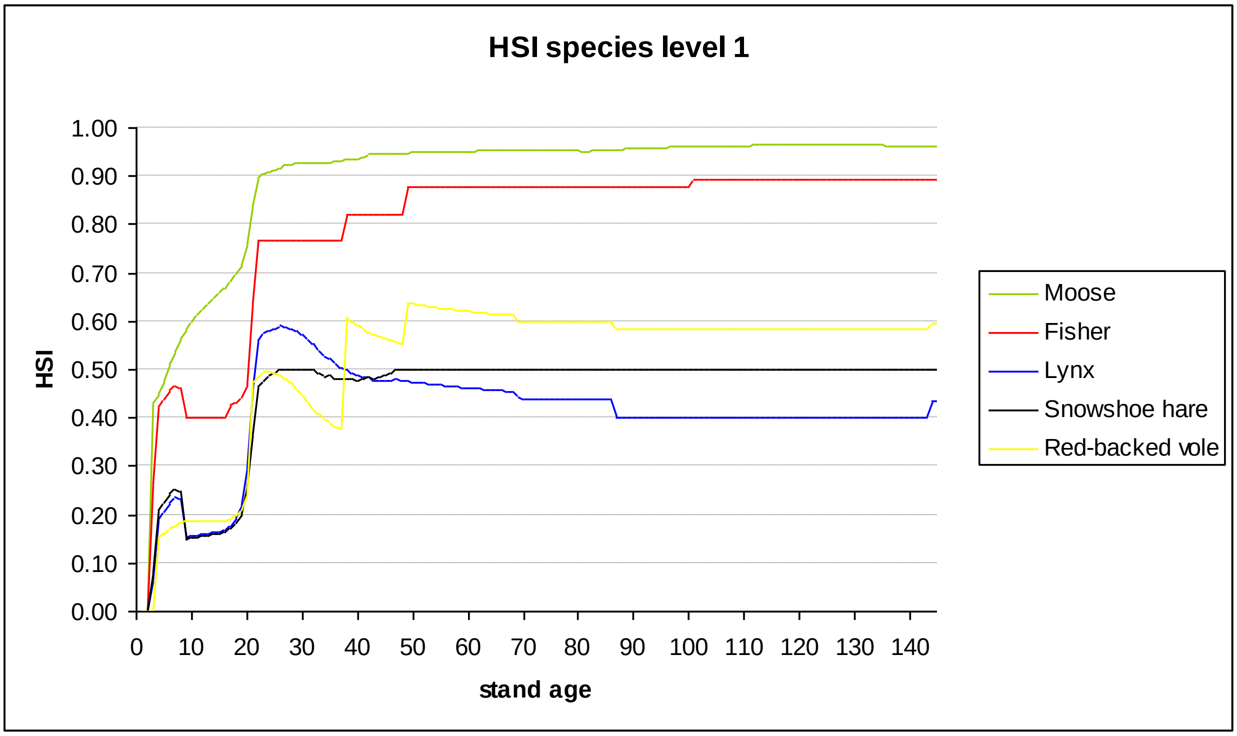
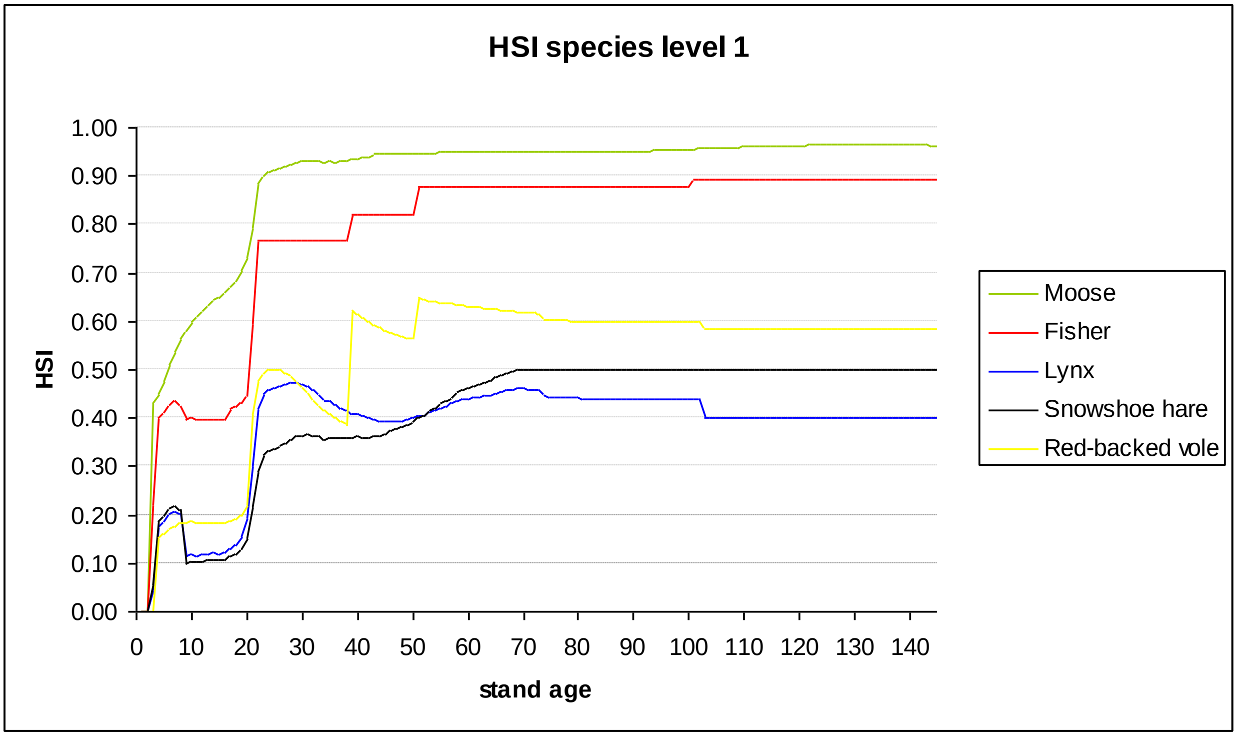


Figure A3-5. HSI values by stand age for ecosite phase b4.



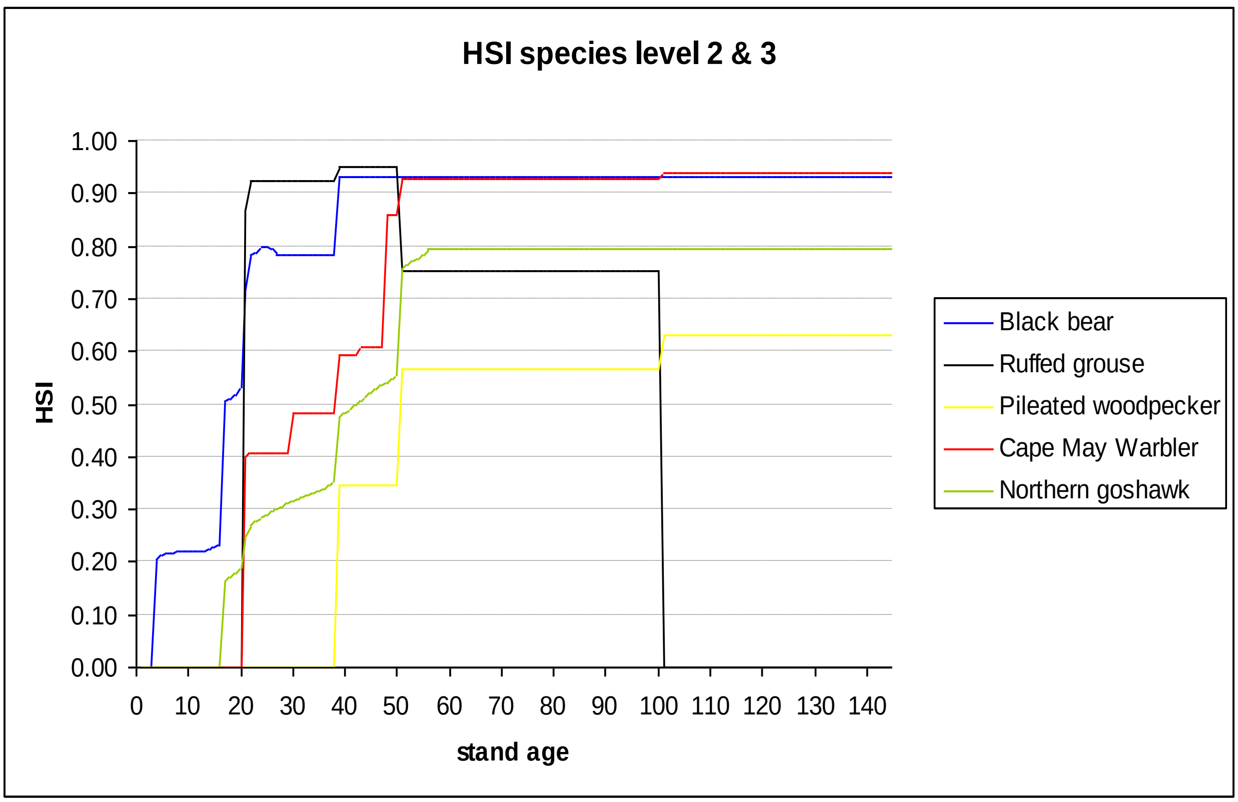
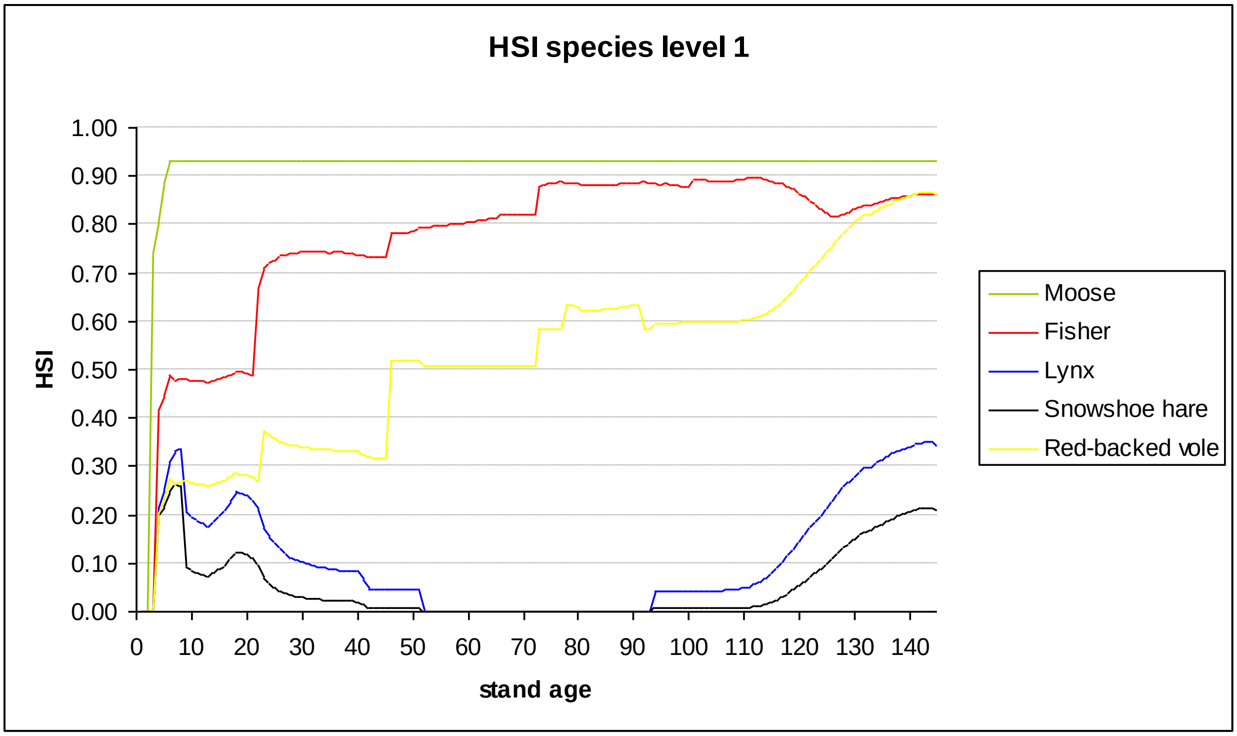


Figure A3-6. HSI values by stand age for ecosite phase c.



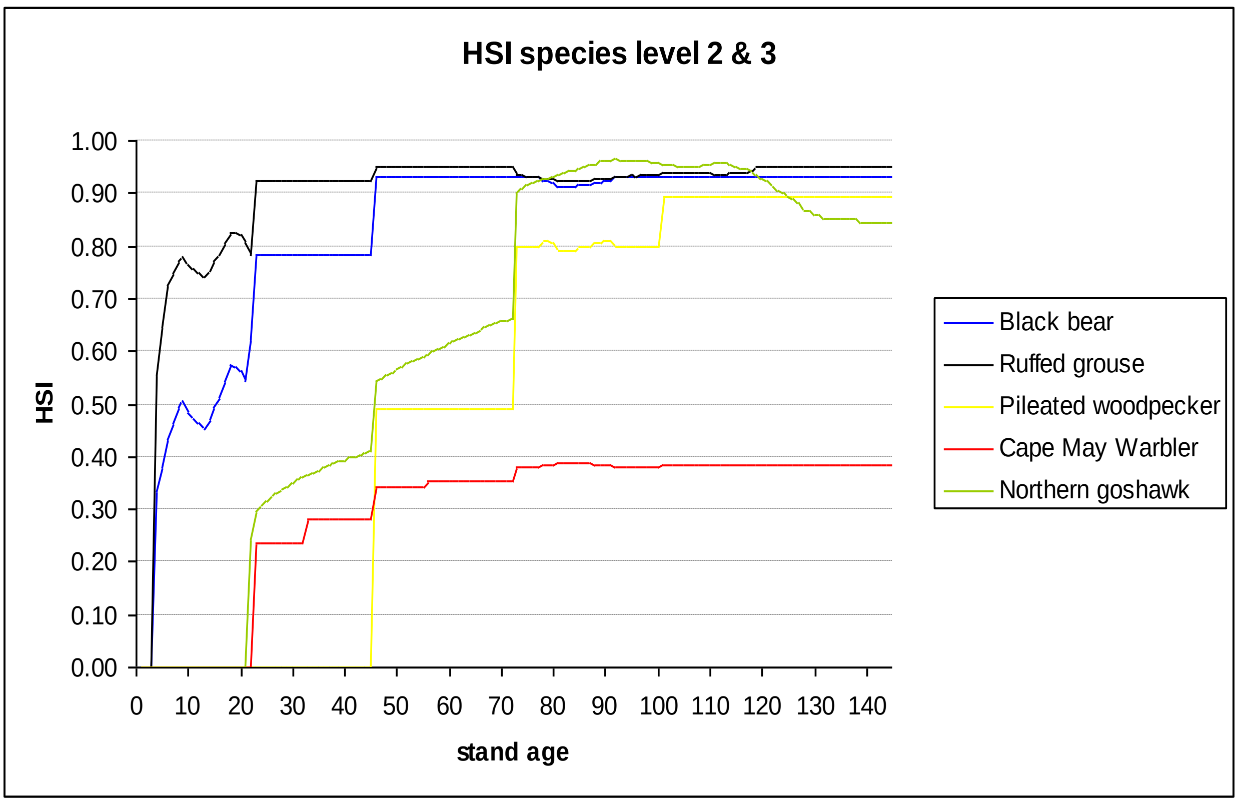
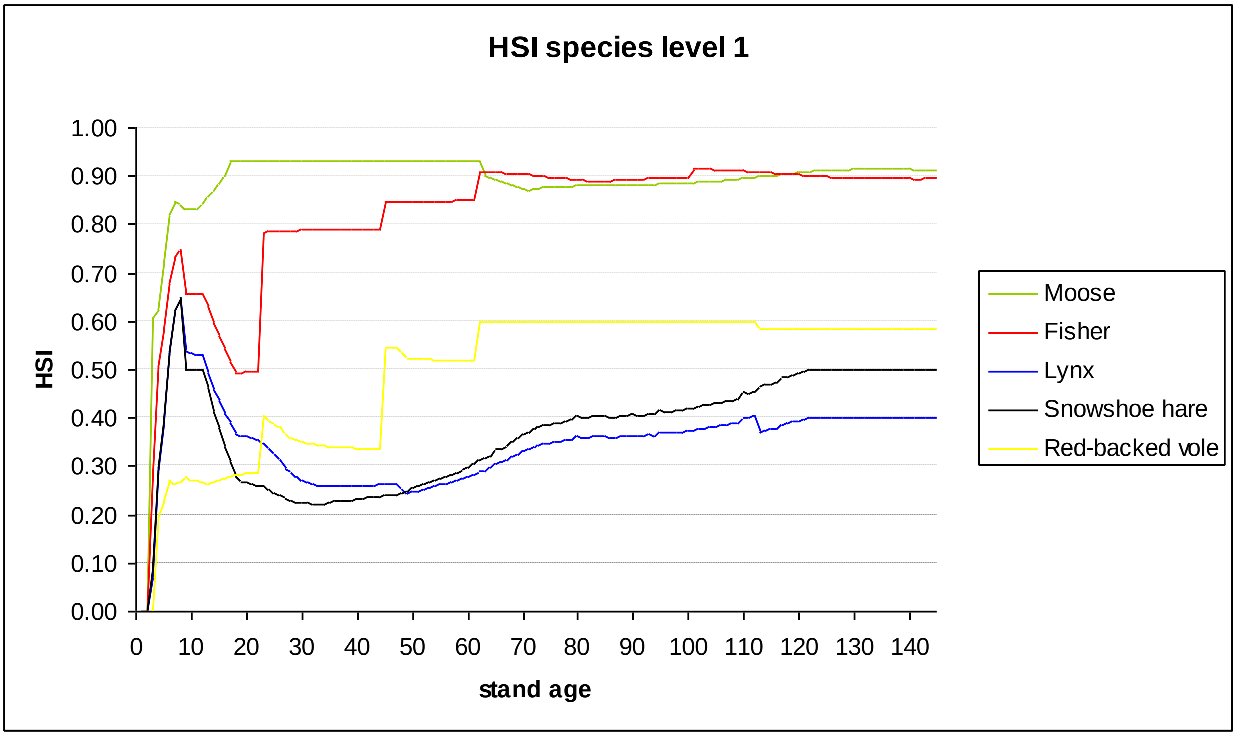


Figure A3-7. HSI values by stand age for ecosite phase d1.



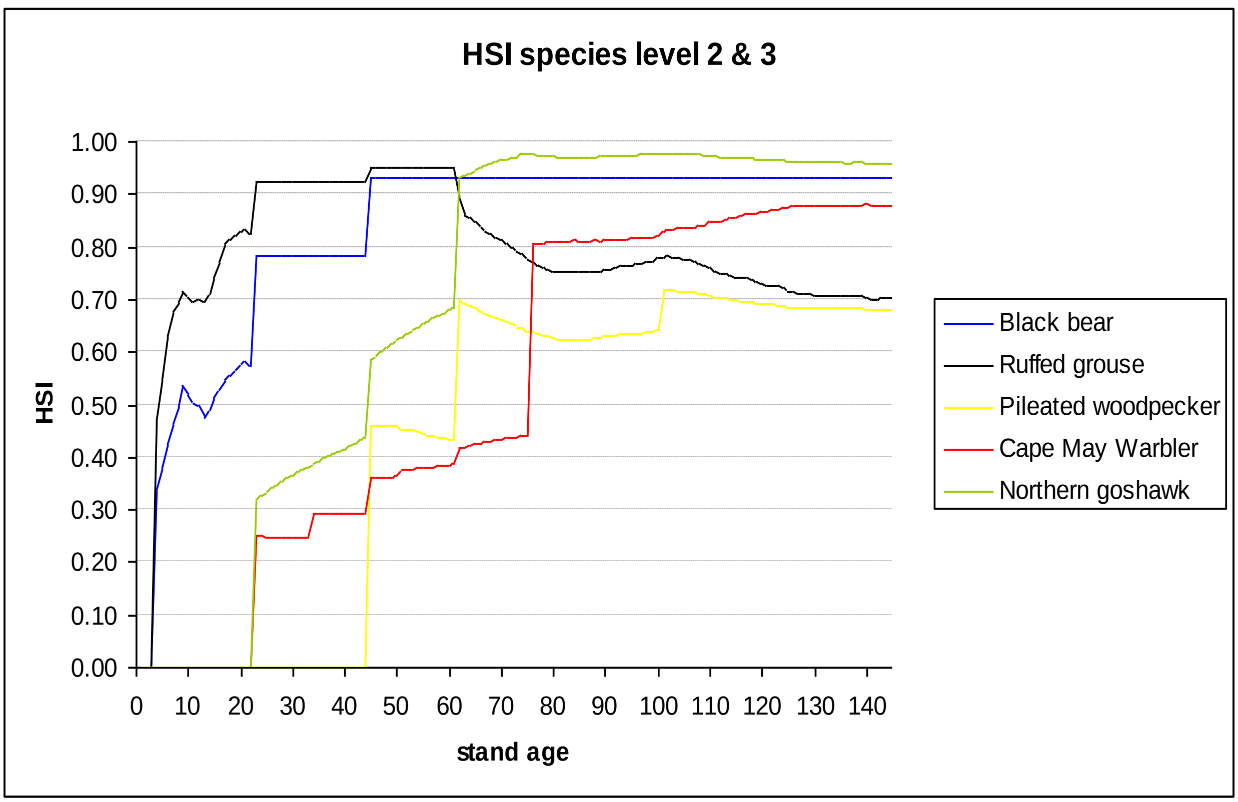
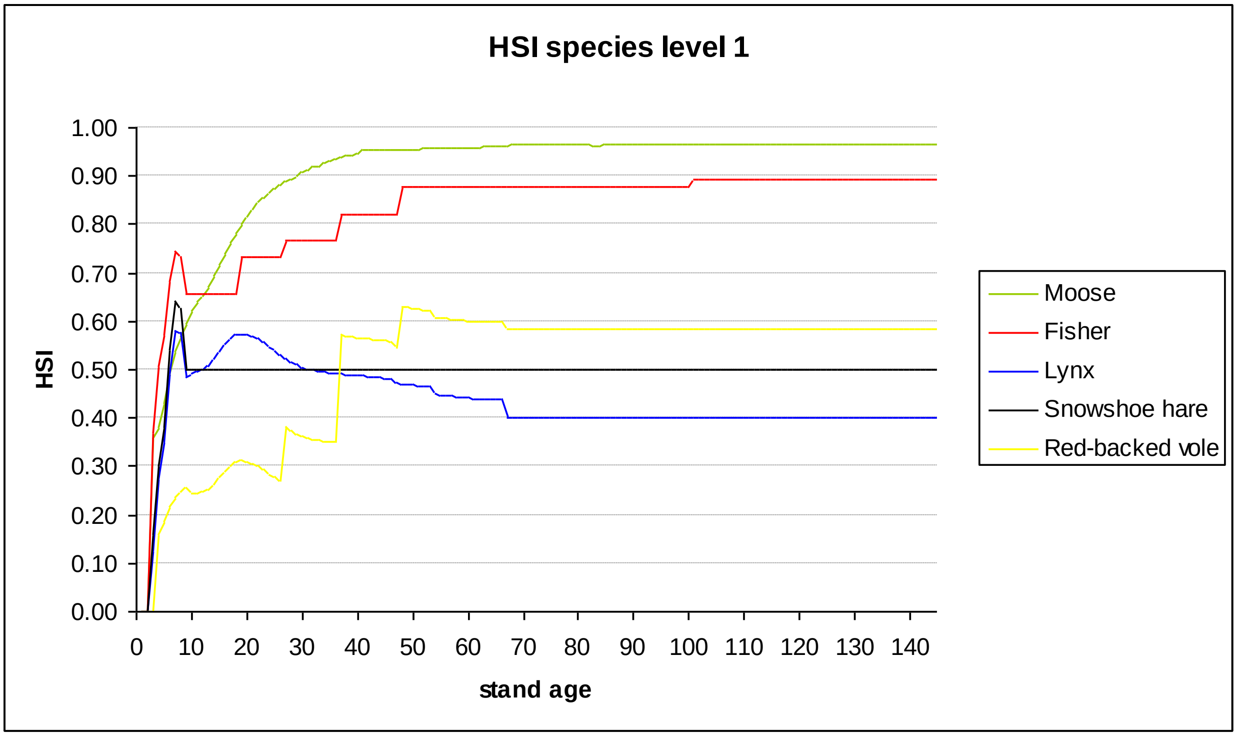


Figure A3-8. HSI values by stand age for ecosite phase d2.



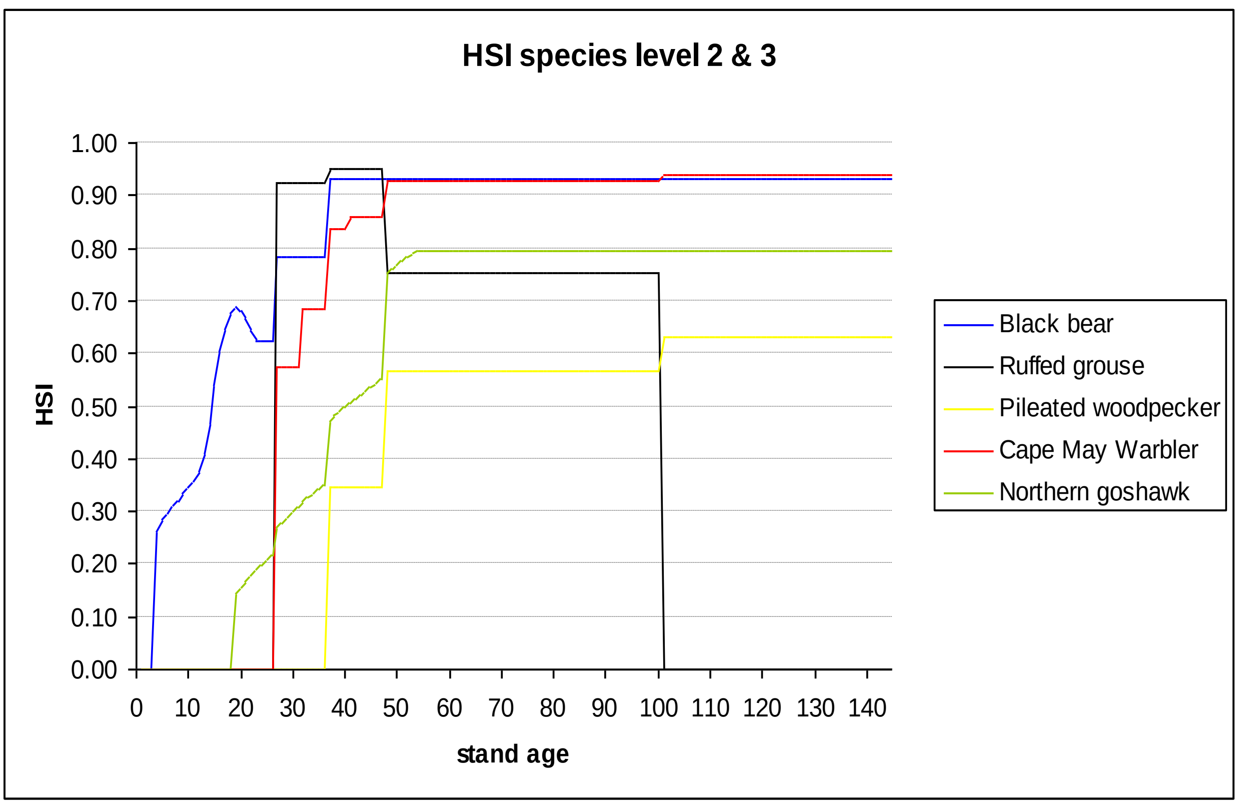
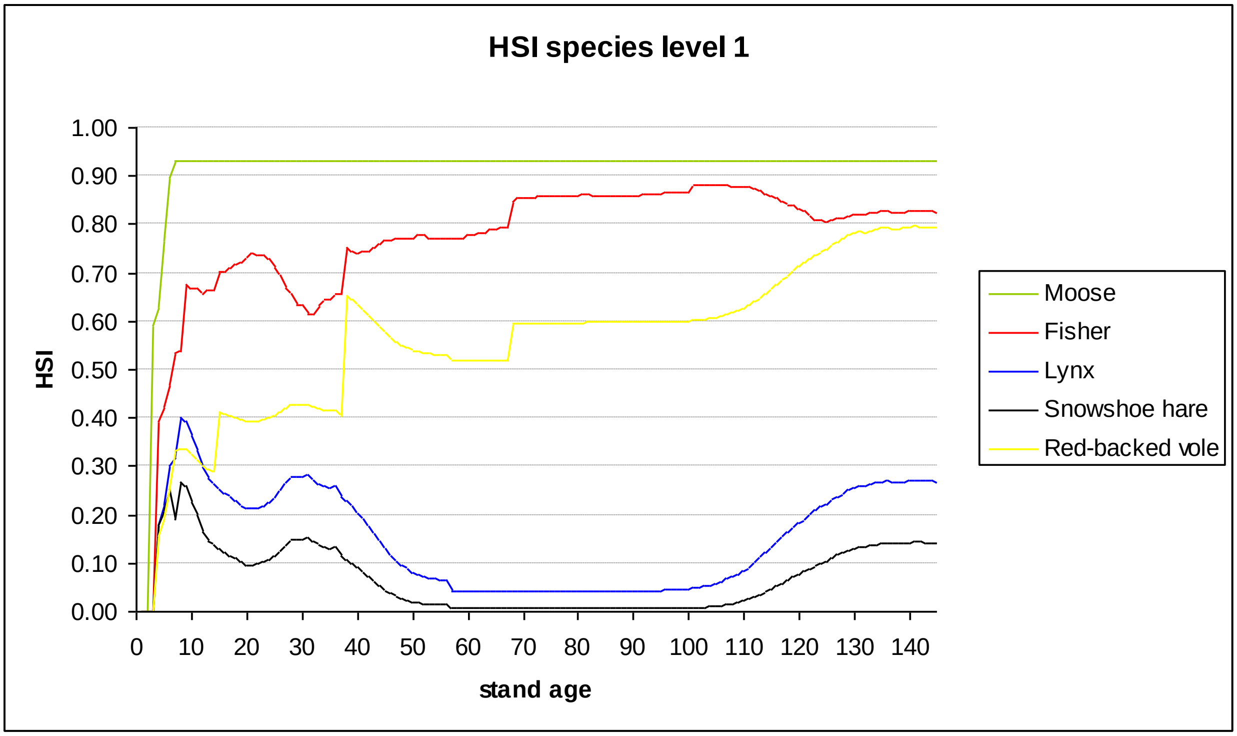


Figure A3-9. HSI values by stand age for ecosite phase d3.



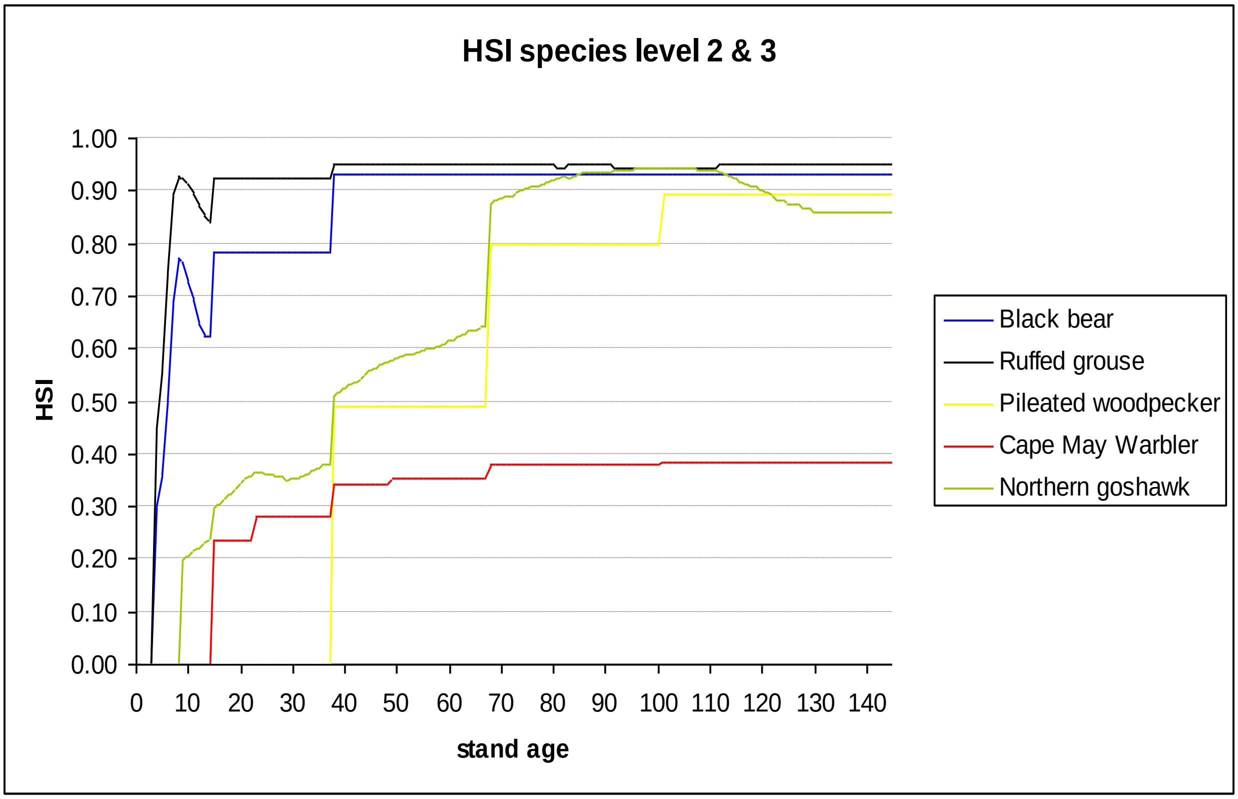
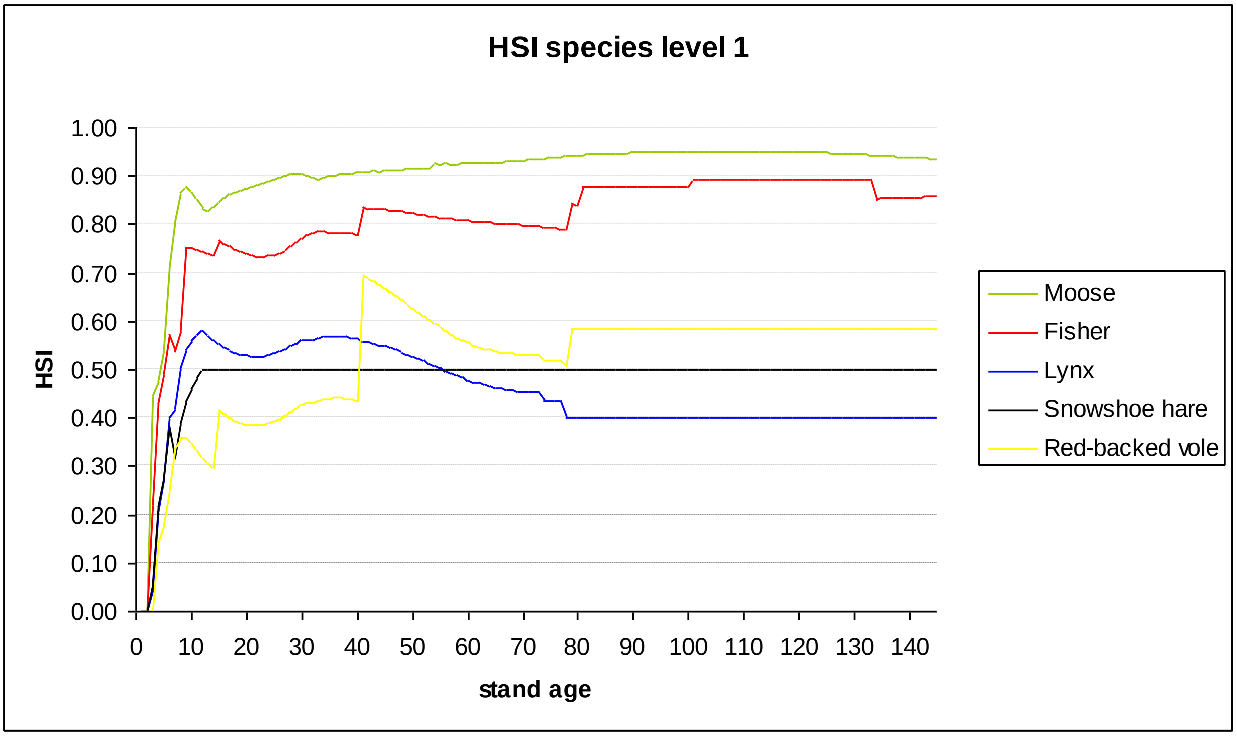


Figure A3-10. HSI values by stand age for ecosite phase e1.



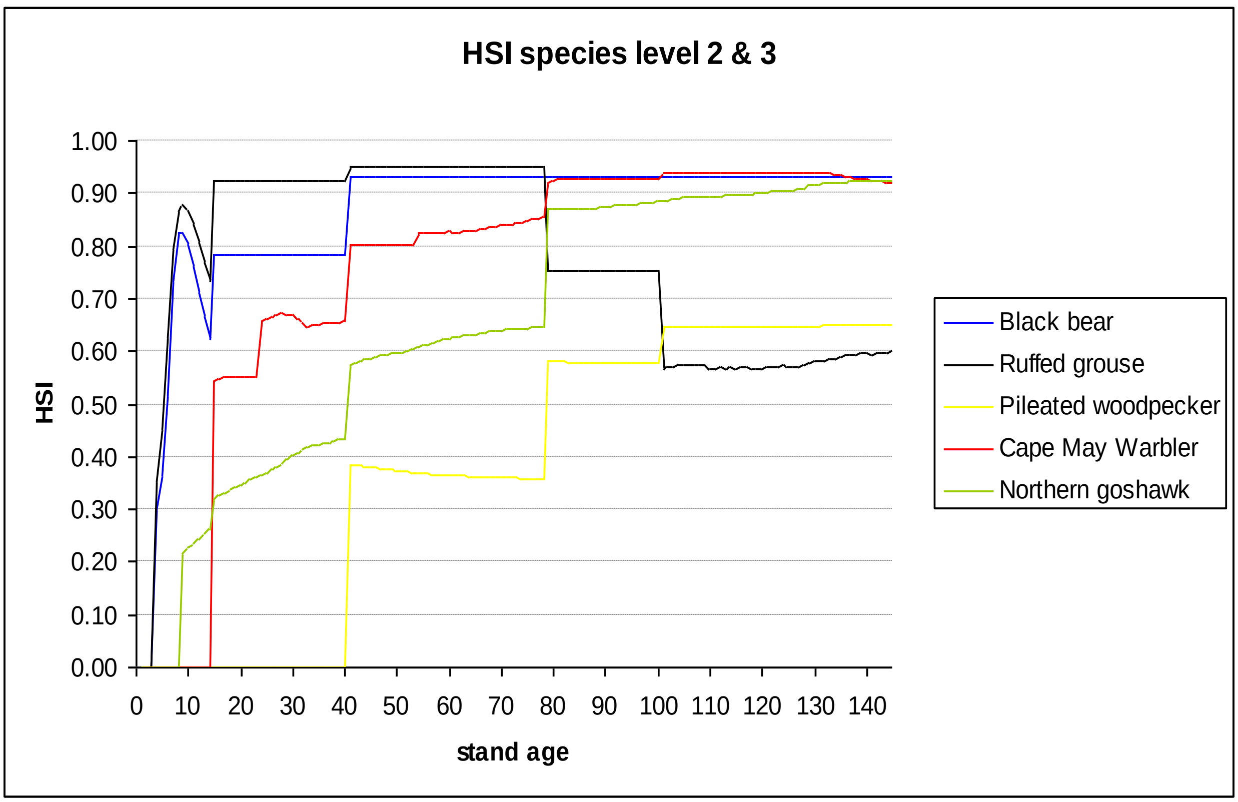
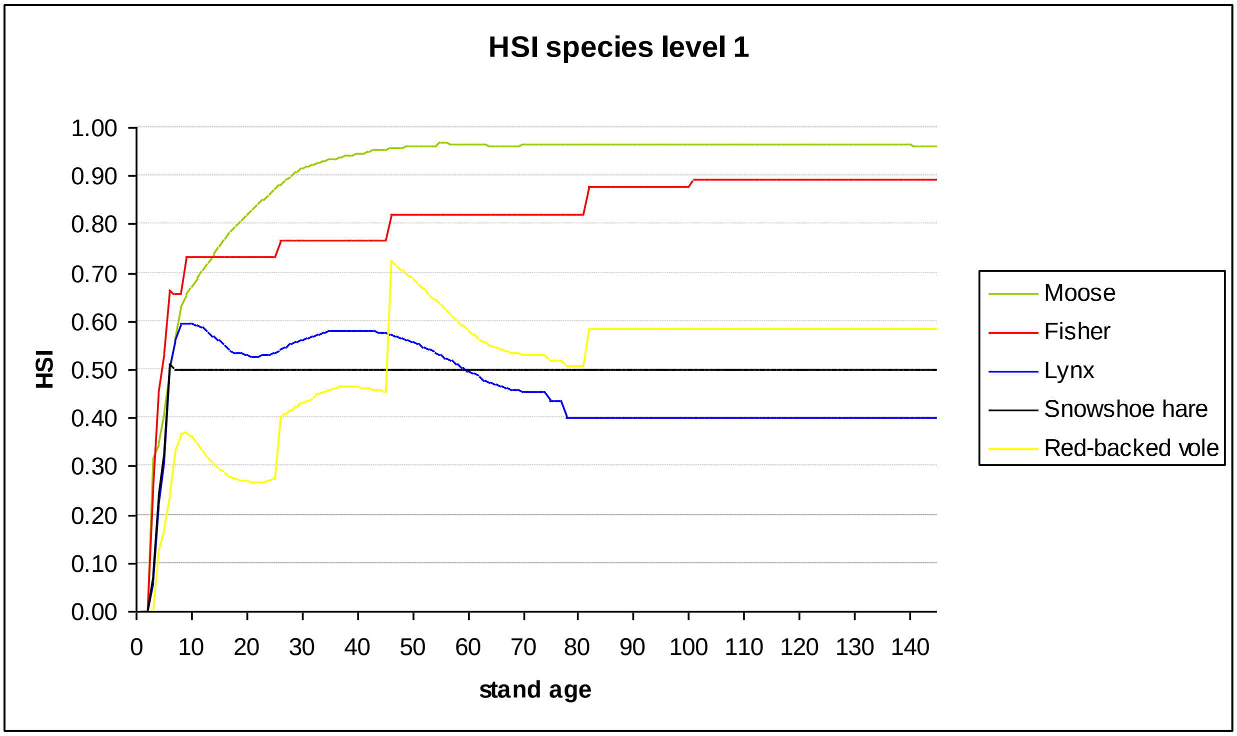


Figure A3-11. HSI values by stand age for ecosite phase e2.



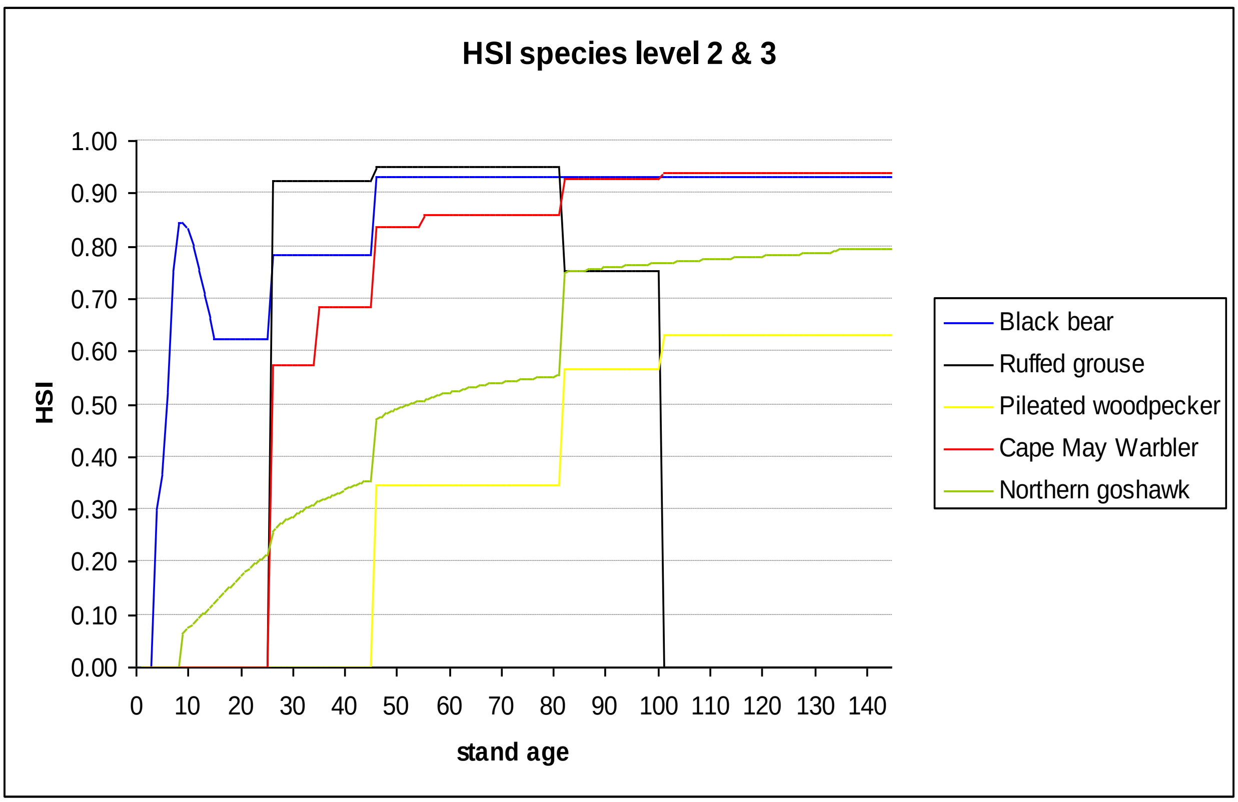
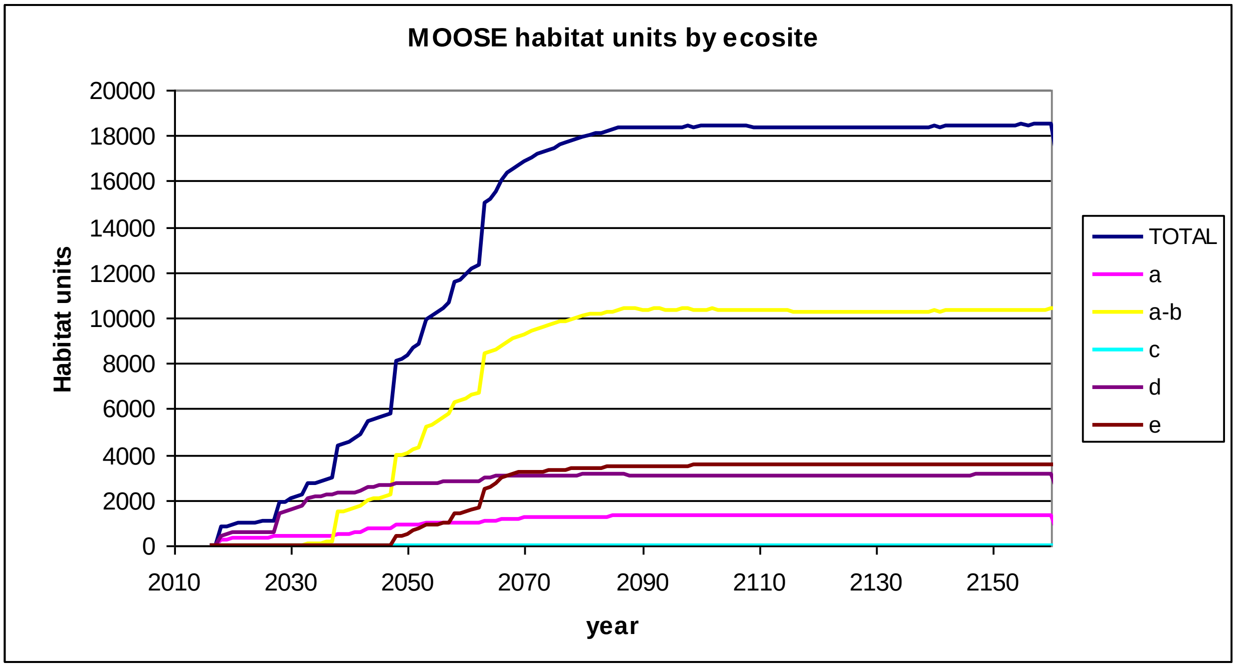


Figure A3-12. HSI values by stand age for ecosite phase e3.

APPENDIX 4: Habitat Units By Ecosite and Reclamation Period



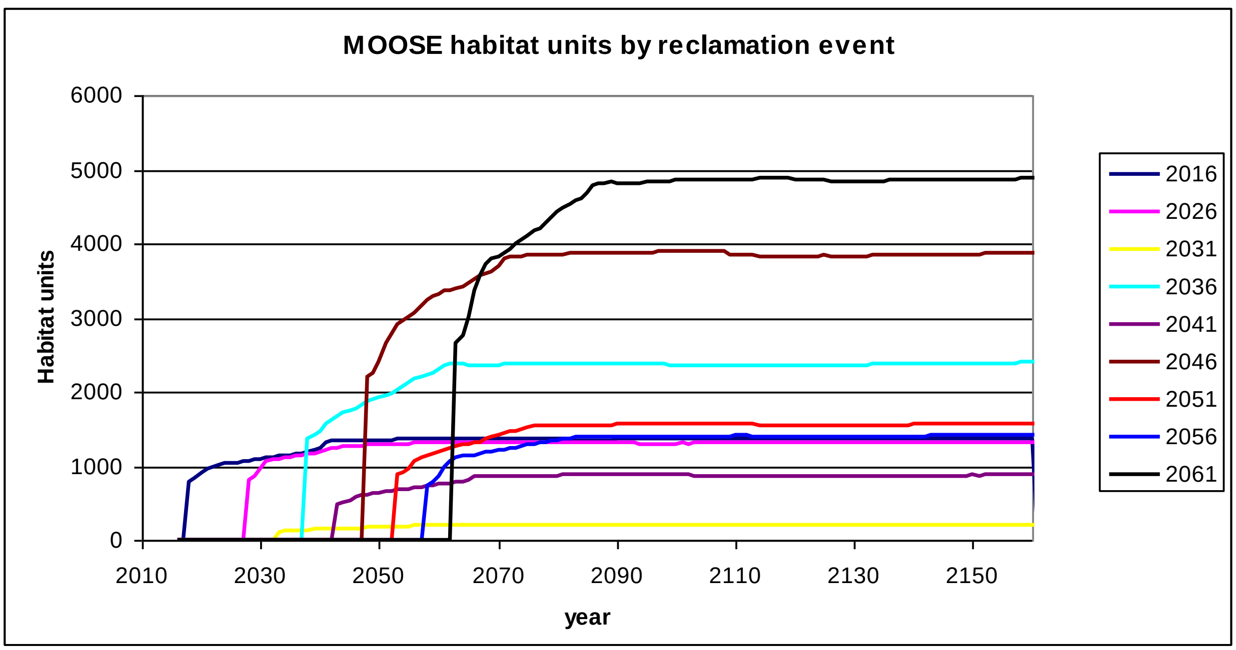
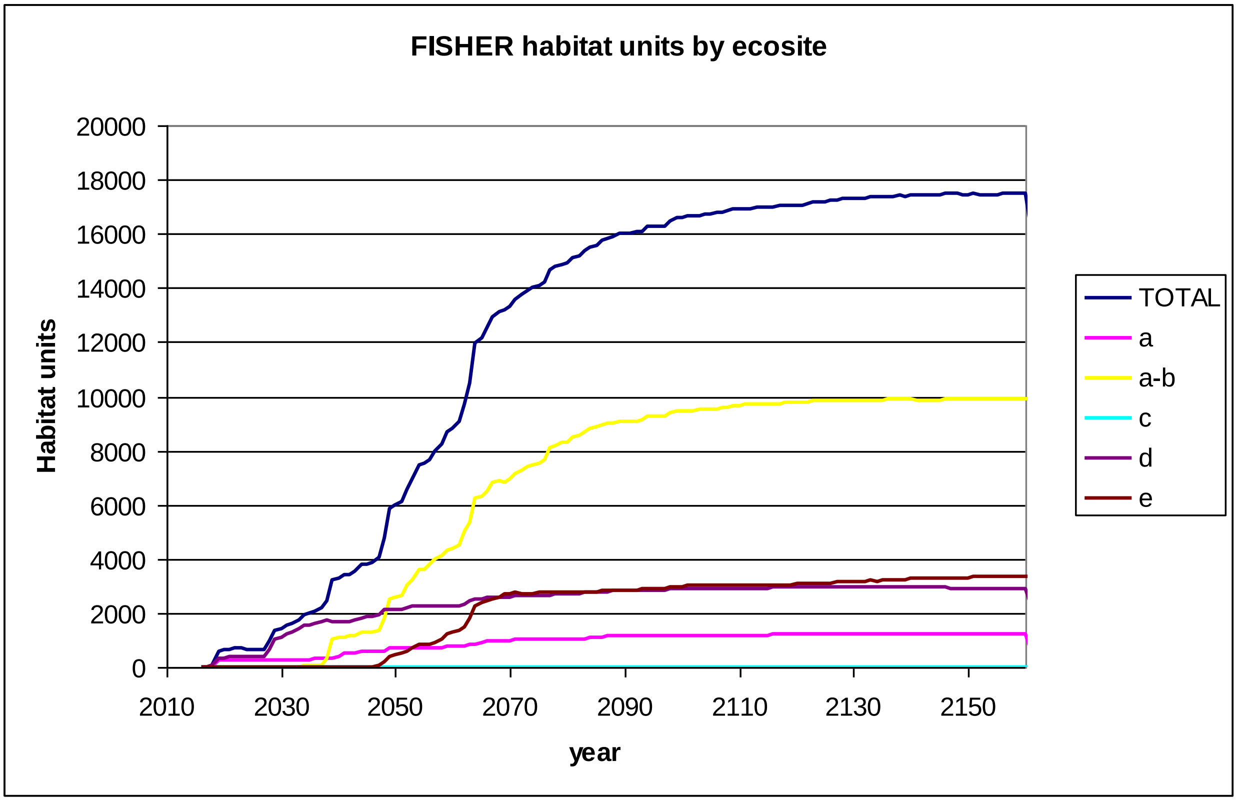


Figure A4-1. Habitat units (ha) for moose by ecosite and timing of reclamation (calendar year).



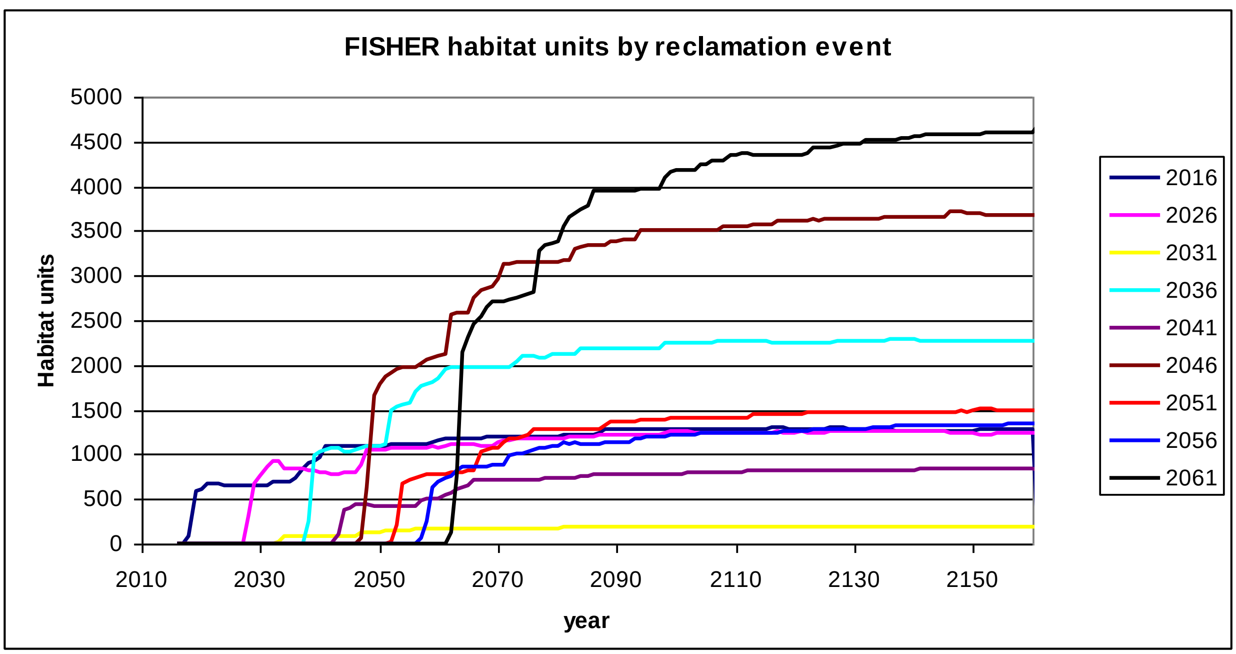
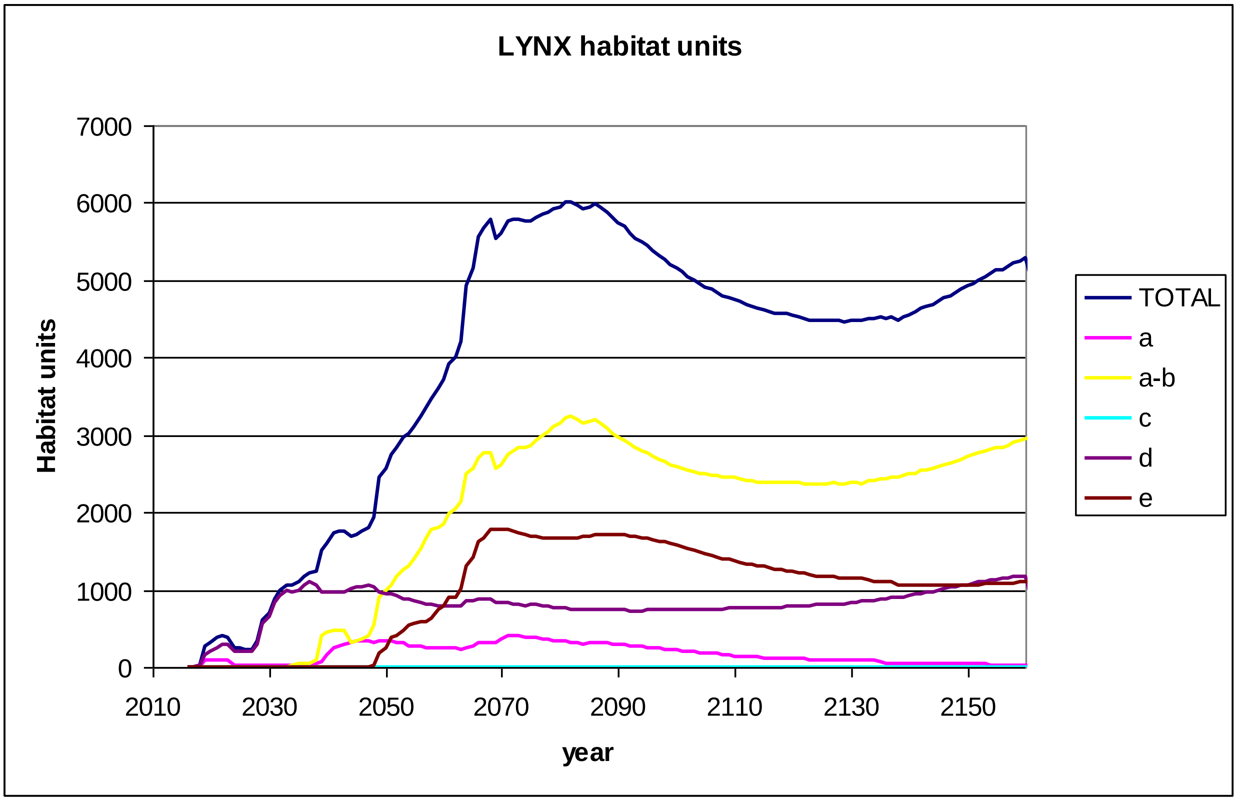


Figure A4-2. Habitat units (ha) for fisher by ecosite and timing of reclamation (calendar year).



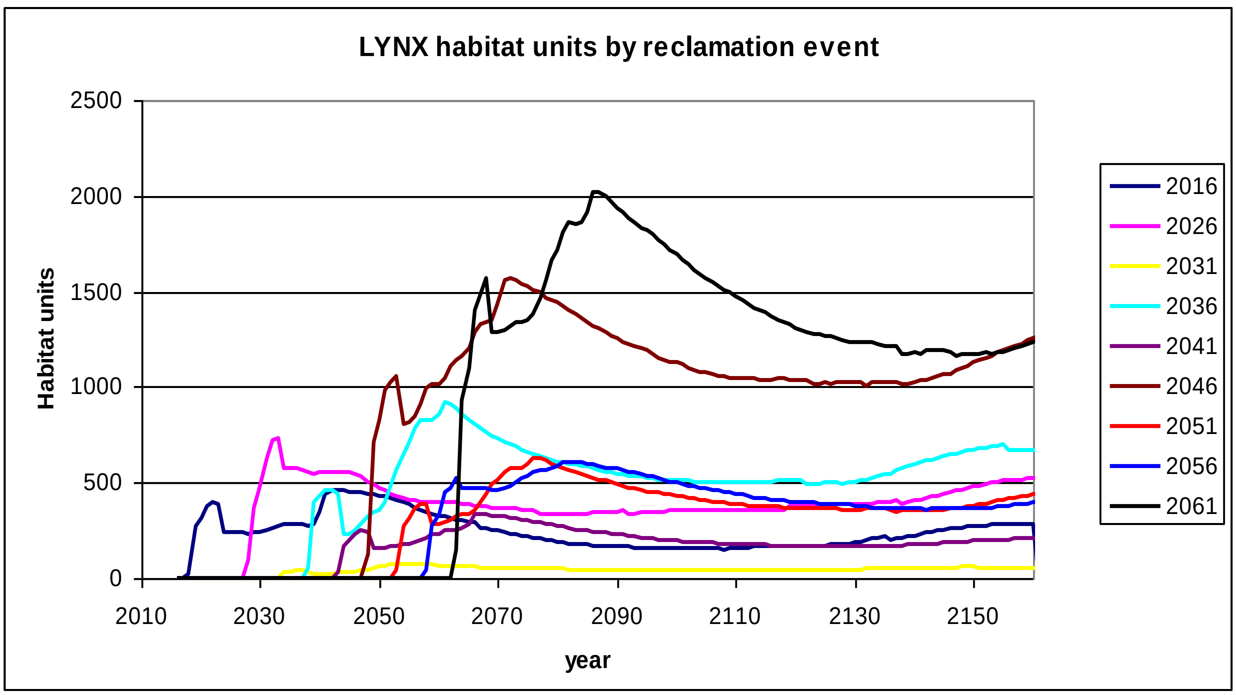
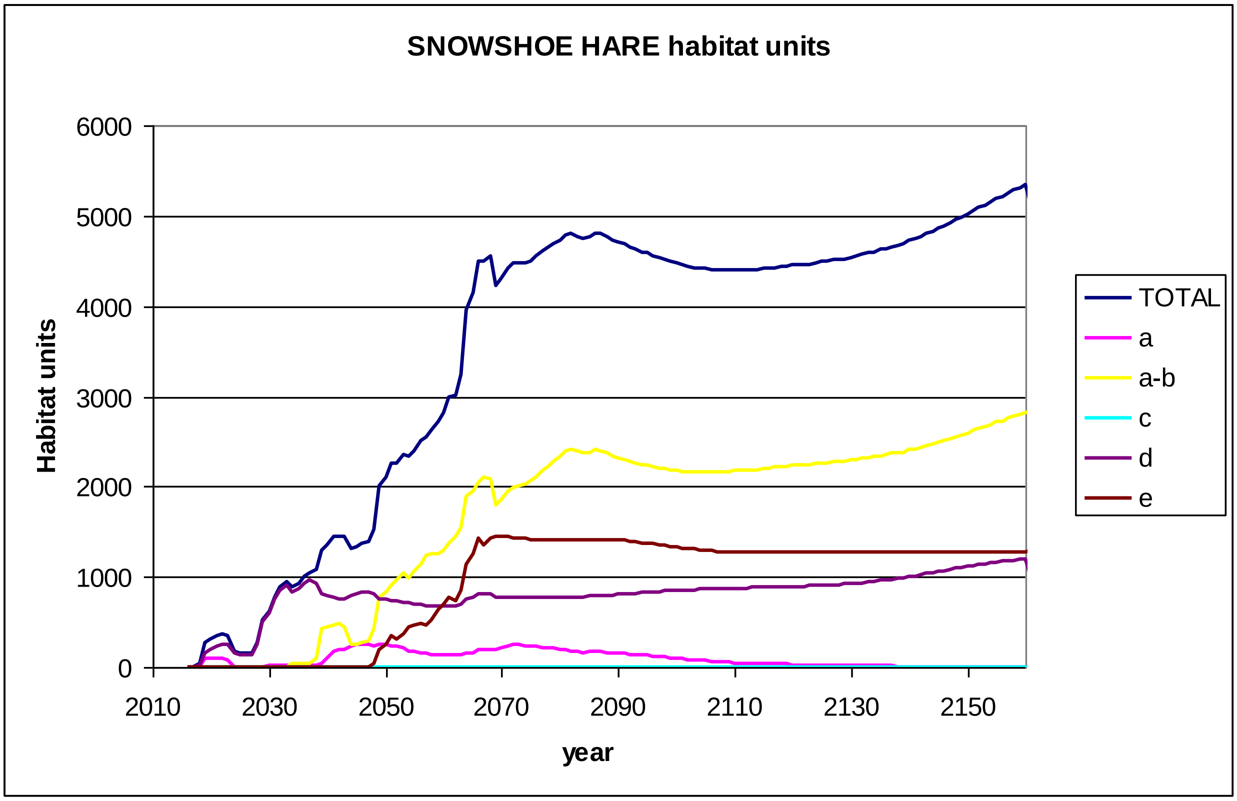


Figure A4-3. Habitat units (ha) for lynx by ecosite and timing of reclamation (calendar year).



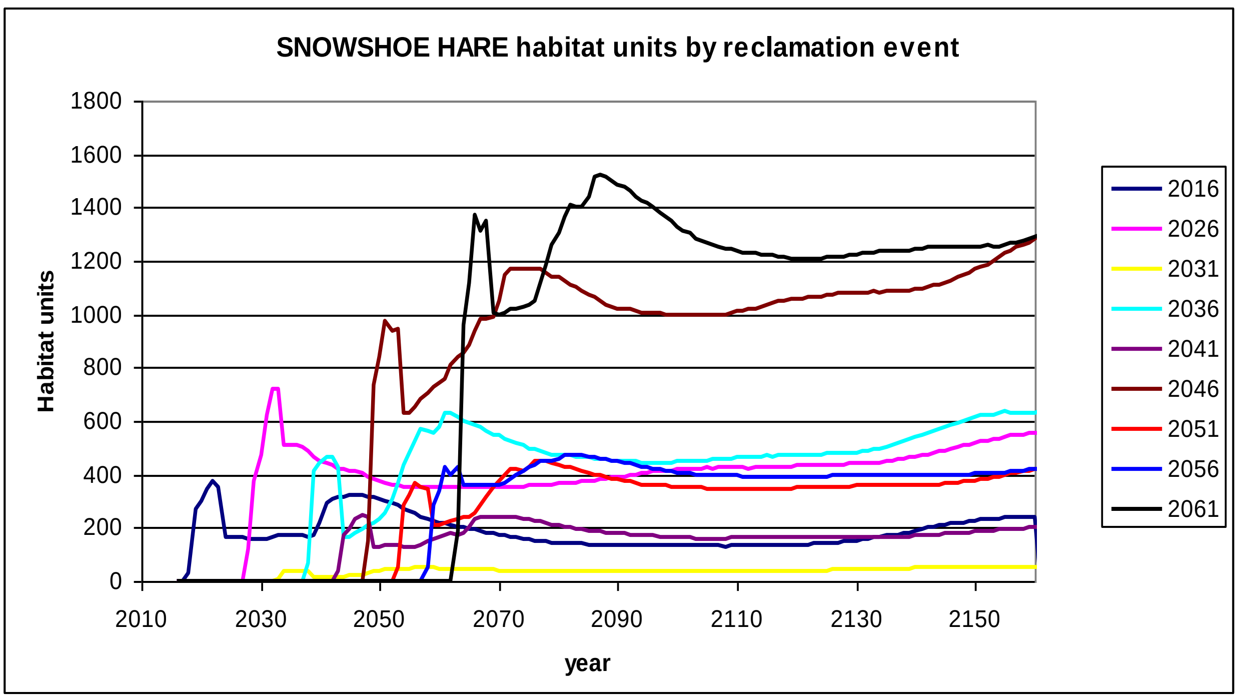
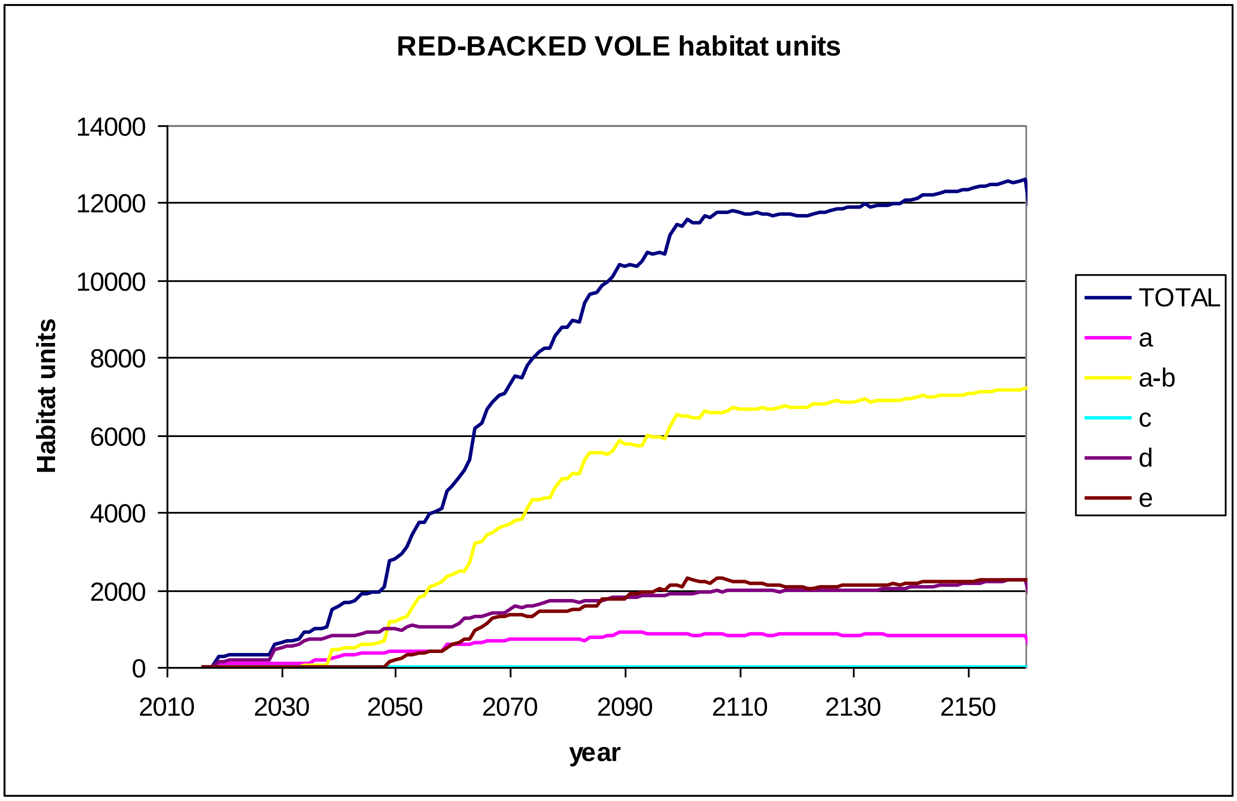


Figure A4-4. Habitat units (ha) for snowshoe hare by ecosite and timing of reclamation (calendar year).



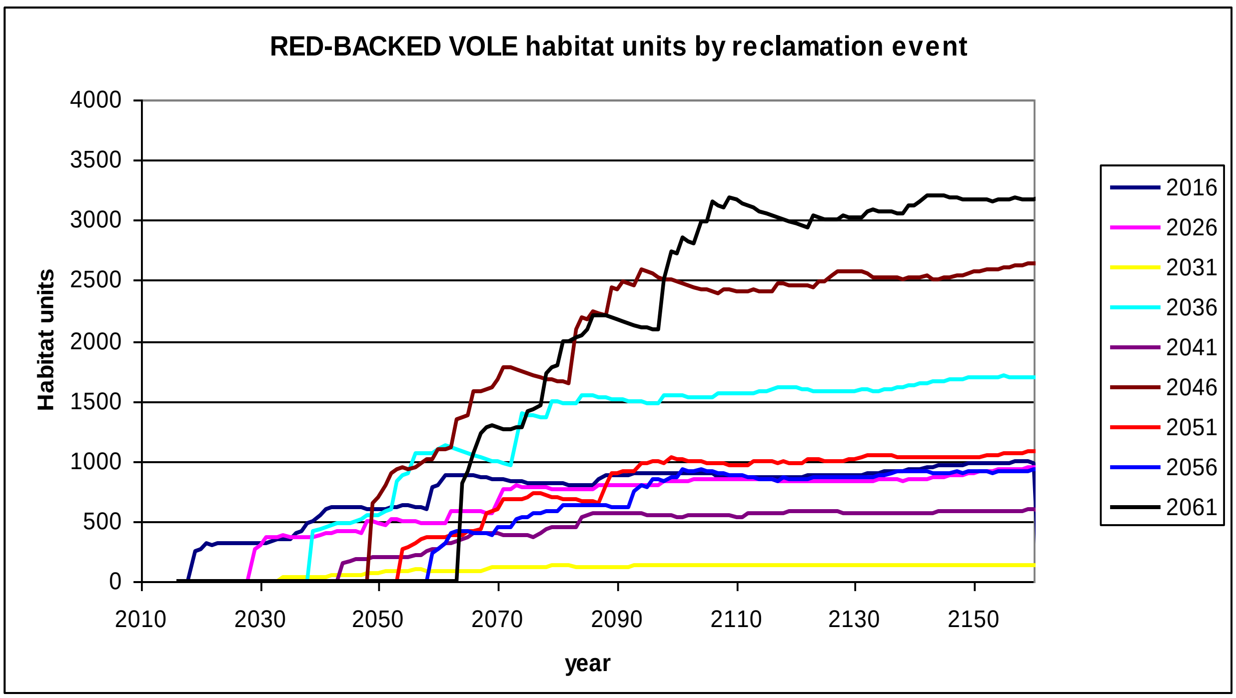
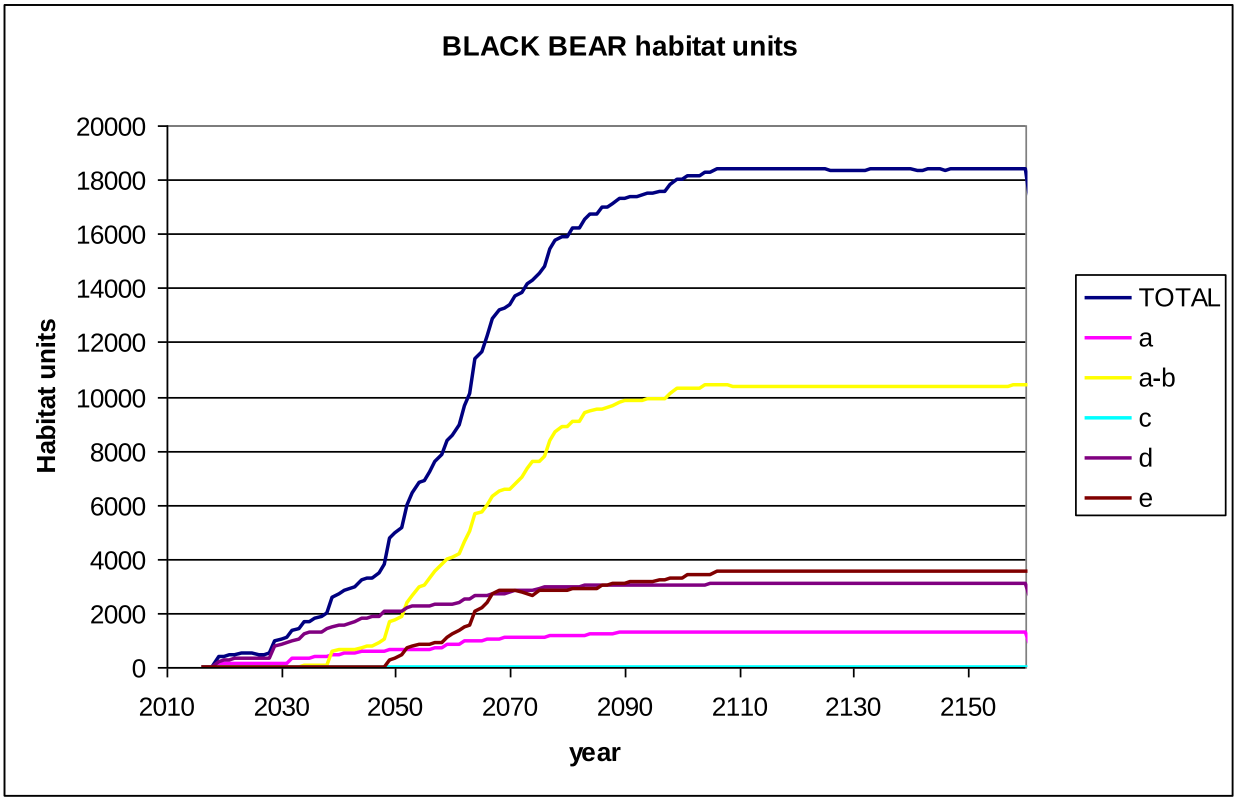


Figure A4-5. Habitat units (ha) for red-backed vole by ecosite and timing of reclamation (calendar year).



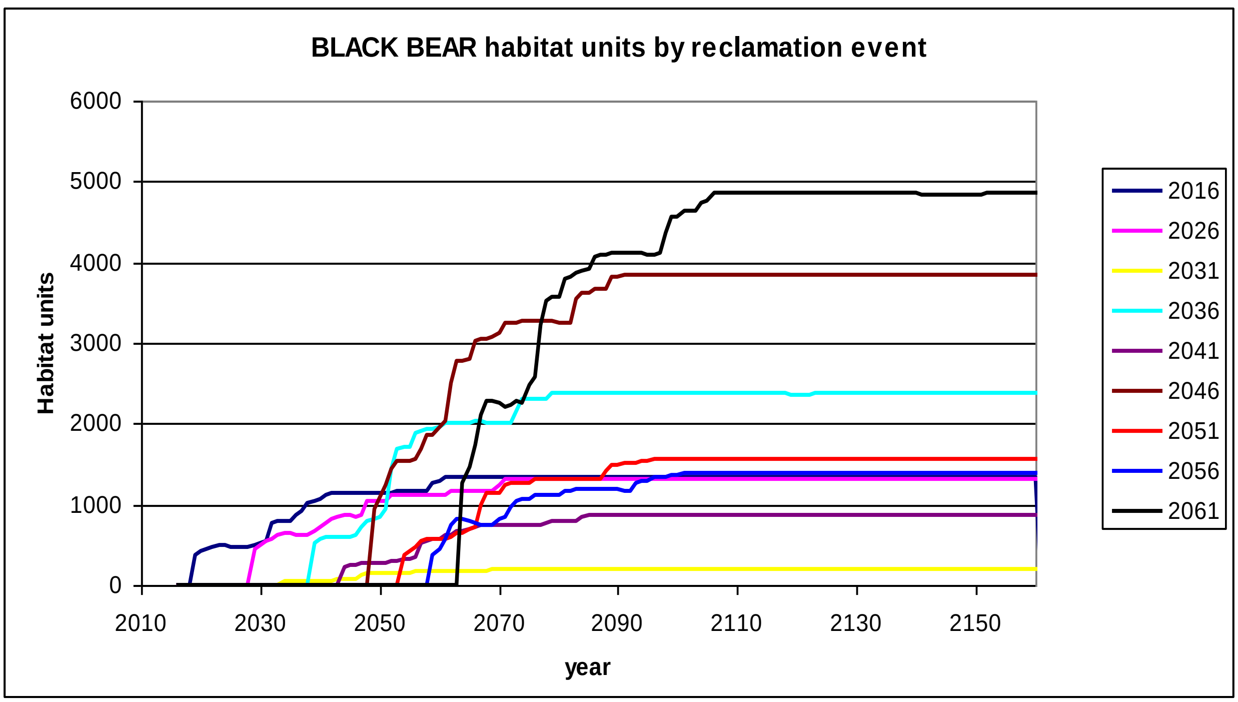
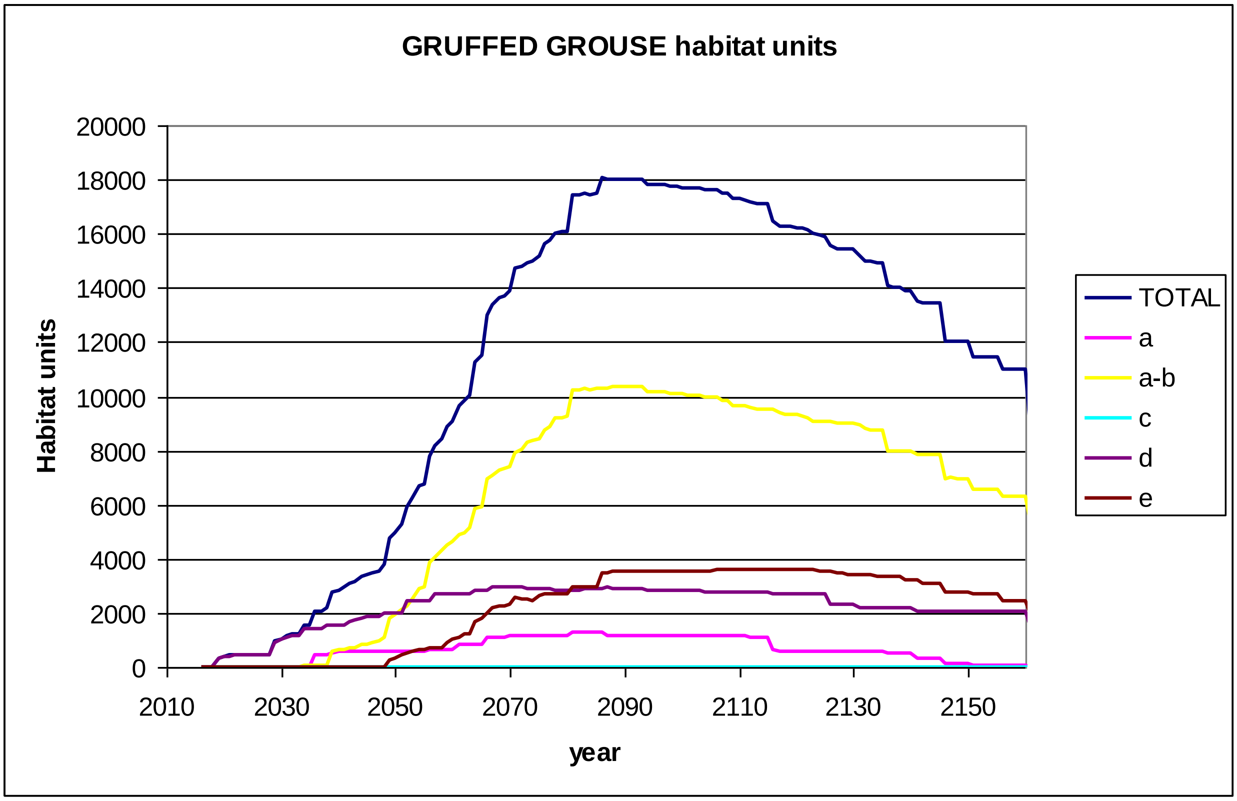


Figure A4-6. Habitat units (ha) for black bear by ecosite and timing of reclamation (calendar year).



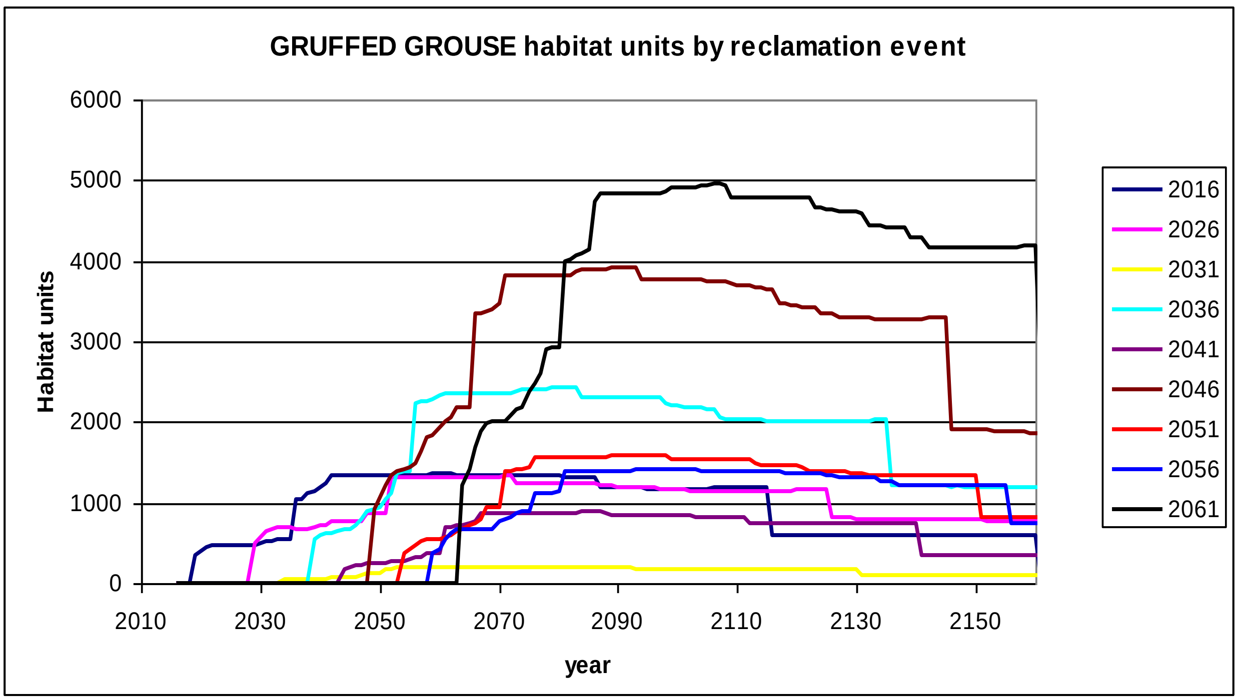
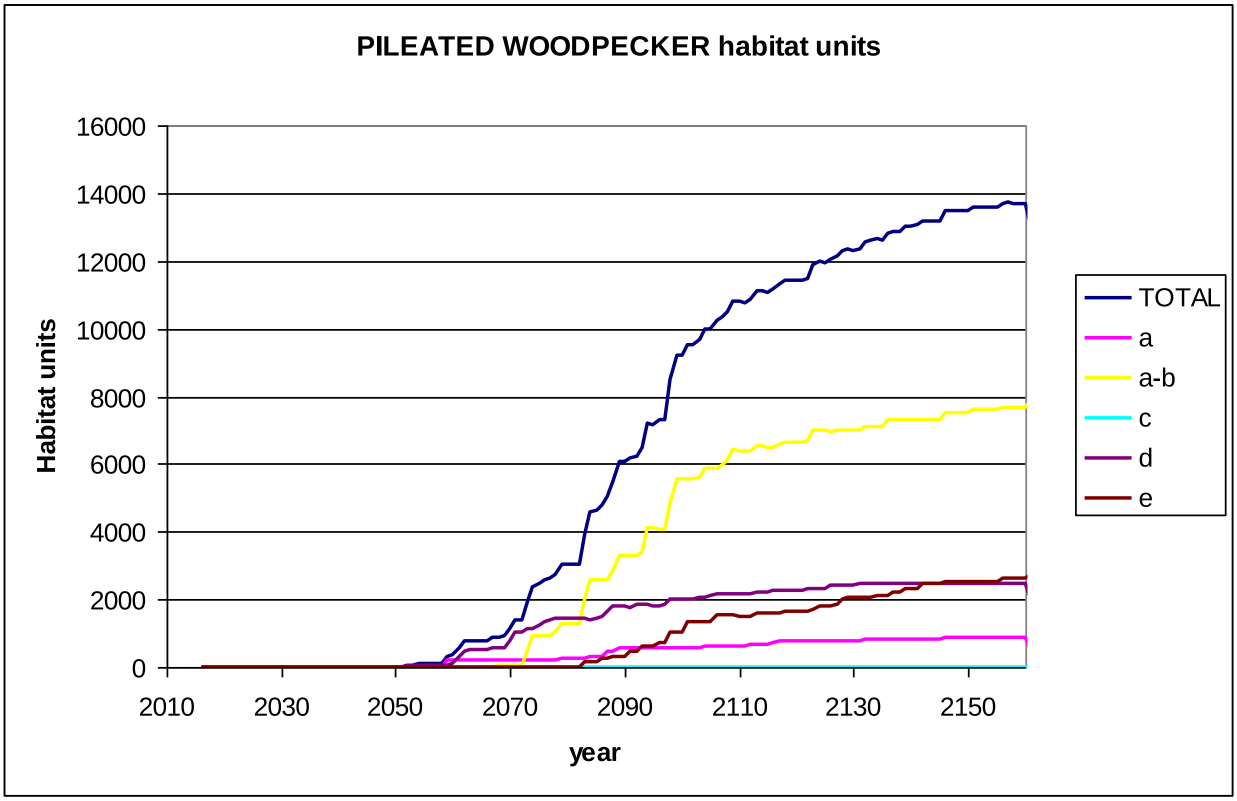


Figure A4-7. Habitat units (ha) for ruffed grouse by ecosite and timing of reclamation (calendar year).



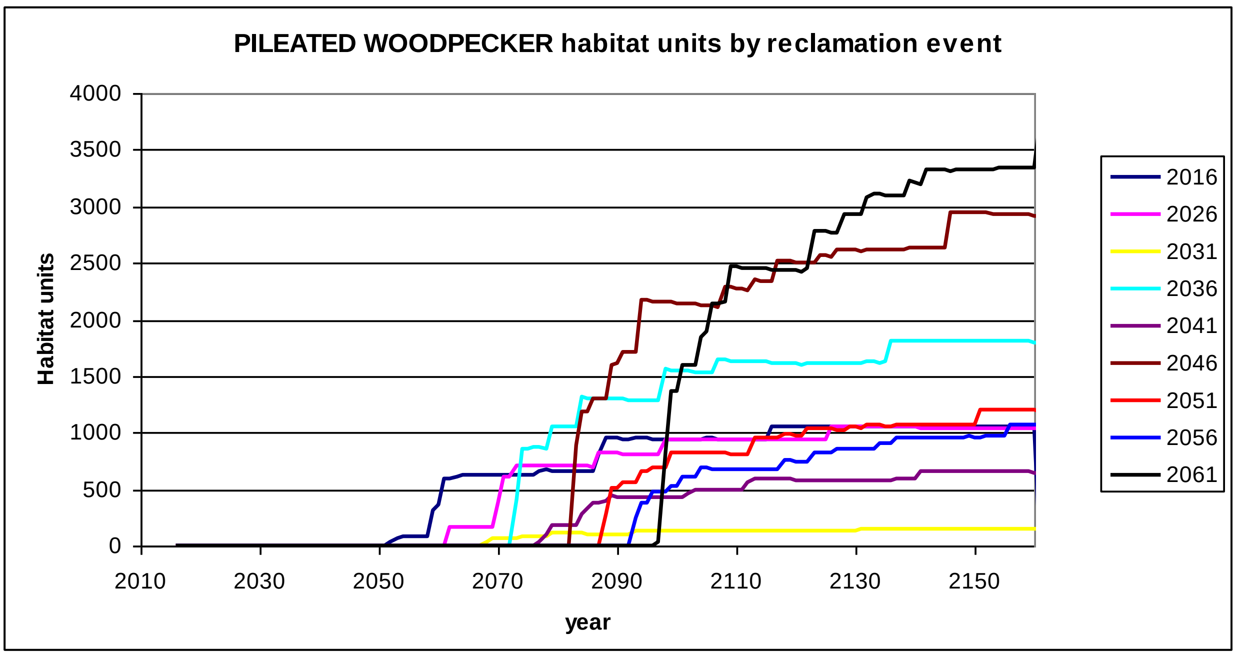
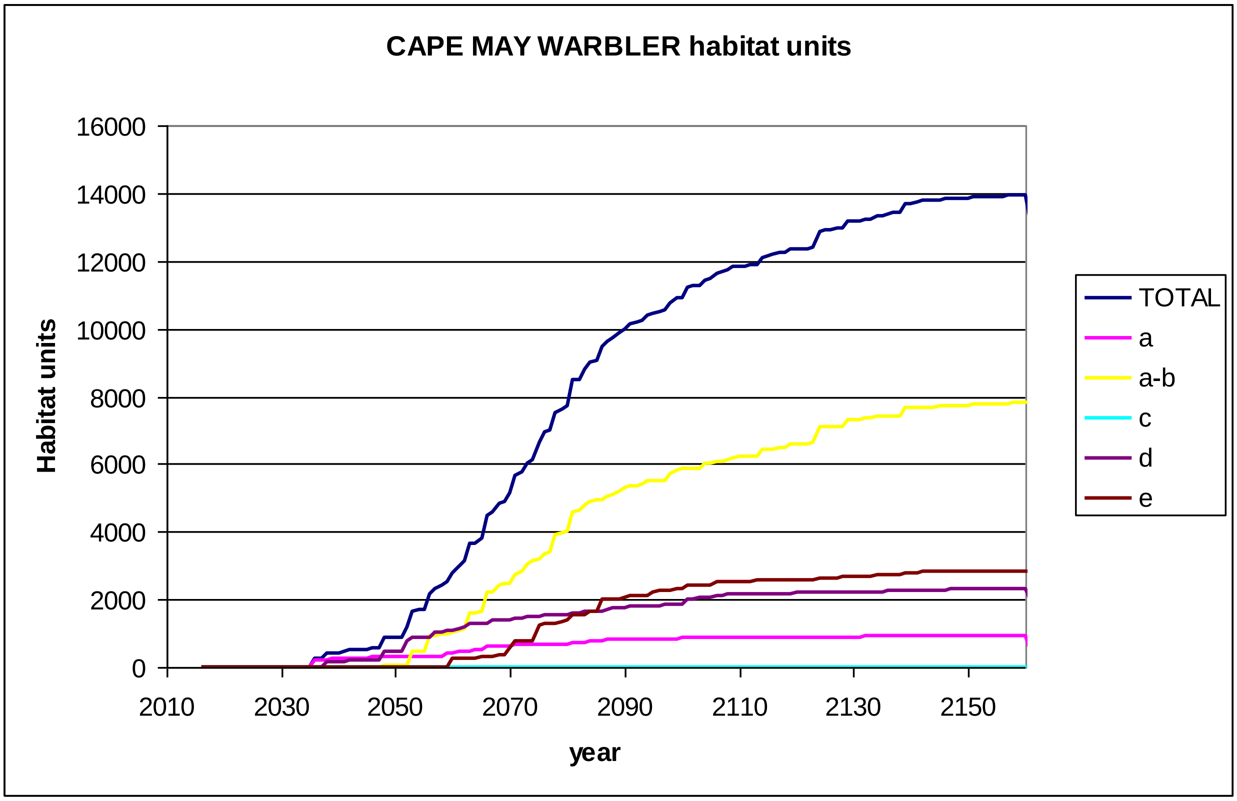


Figure A4-8. Habitat units (ha) for pileated woodpecker by ecosite and timing of reclamation (calendar year).



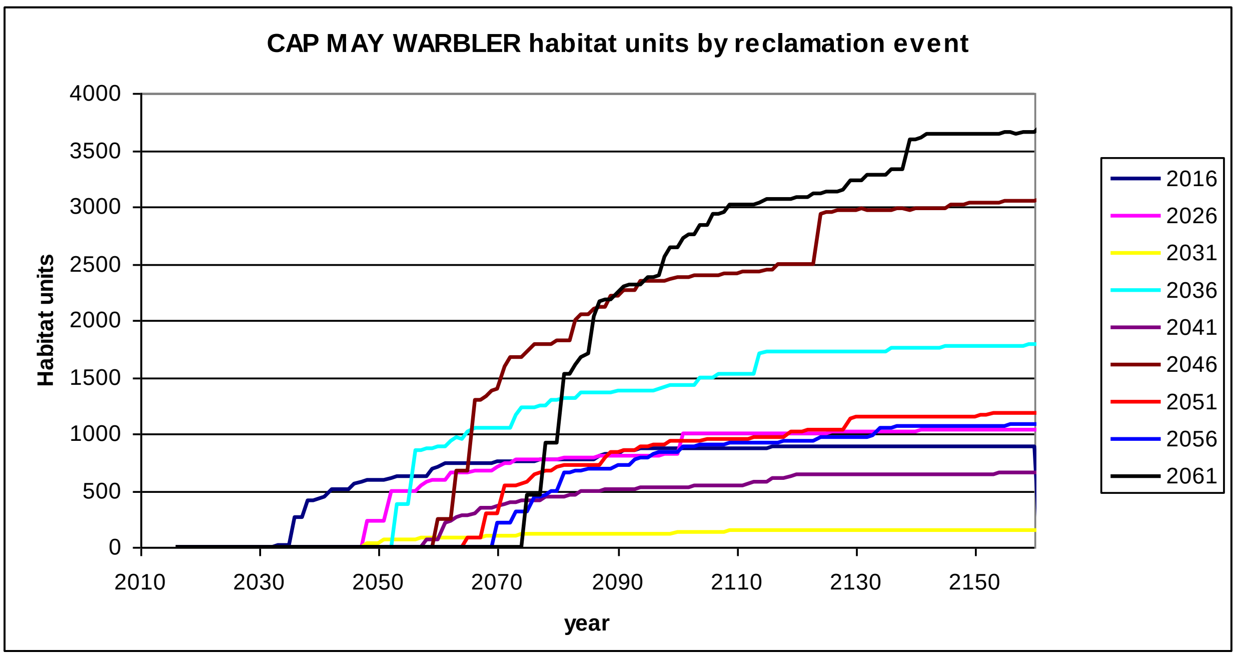
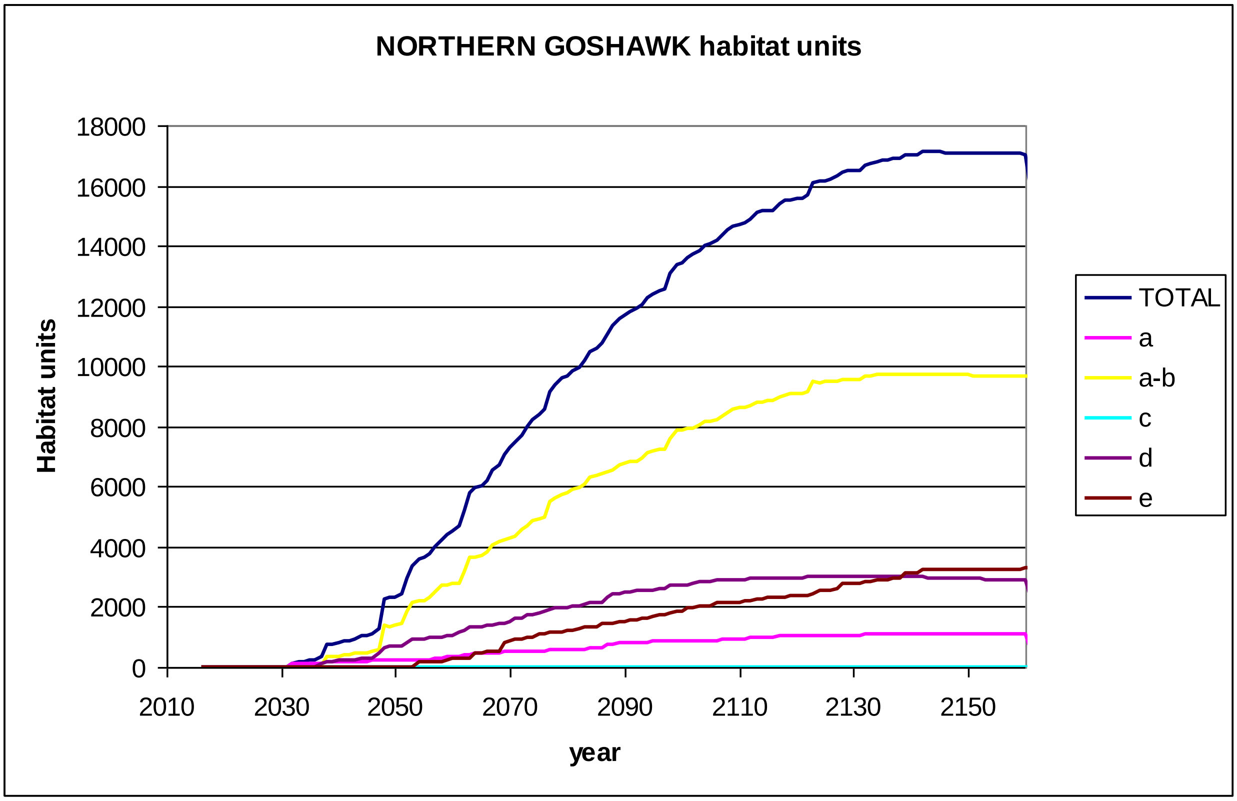


Figure A4-9. Habitat units (ha) for cape may warbler by ecosite and timing of reclamation (calendar year).



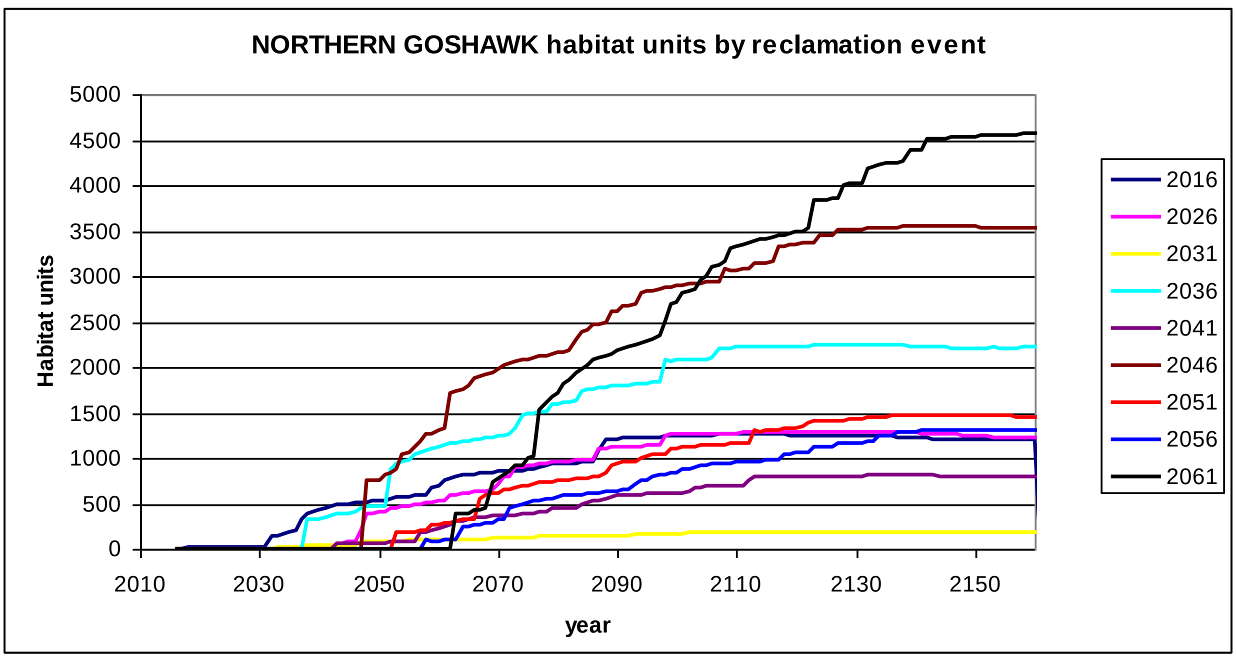


Figure A4-10. Habitat units (ha) for northern goshawk by ecosite and timing of reclamation (calendar year).