Supplementary Methods

Carlson, Matt, and David Browne. 2015. **The Future of Wildlife Conservation and Resource Development in the Western Boreal Forest: A technical report on cumulative effects modeling of future land use scenarios**. Canadian Wildlife Federation, Kanata, Ontario, Canada.

**References cited in this supplementary document are provided in the main report.

Table of Contents

1 Land Cover

Land cover was assessed using the Earth Observation for Sustainable Development (EOSD) land cover data set (Centre for Topographic Information 2009a), which is based on classified Landsat 5 and Landsat 7 orth-images taken between 1997 and 2005 (with 80% of the images taken within 1 year of the year 2000). The data set was selected for the project because it was the most current land cover data with coverage across the study area. Land cover classes within the EOSD data set (Centre for Topographic Information 2009b) were aggregated to create 14 land cover classes for the project. All wetlands were assumed to be peatlands, given that mineral wetlands are absent from the Boreal Plains ecozone and account for only 0.5% of wetlands in the Taiga Plains ecozone (Wiken et al. 2003). The 30-m resolution EOSD data set was spatially aggregated to 1-km resolution based on the most common land cover type across EOSD pixels with each 1-km block. Aggregation to 1-km resolution was required to manage the size of the data set due to the scope of the study area. The EOSD data set did not specify agricultural land, which instead was identified using the land cover data set created by the National Land and Water Information Service of Agriculture and Agri-Food Canada. The area of lakes and rivers was assessed using the National Hydro Network dataset (Centre of Topographic Information 2004), as was the length of streams (405,120 km). Stream length was applied during simulations to track stream fragmentation from culverts associated with roads. The resulting land cover type used in the model and their total area within the study region are described in Table 1.

Table 1. Description and initial area of land cover types in the study area.

Land cover type	Corresponding GeoBase cover types	Description	Area (ha)
Deciduous forest	Broadleaf Dense, Broadleaf Open, Broadleaf Sparse	Predominantly forested areas with crown closure ≥ 10% and deciduous trees accounting for ≥ 75% of total basal area.	13,973,186
Coniferous forest	Coniferous Dense, Coniferous Open, Coniferous Sparse	Predominantly forested areas with crown closure ≥ 10% and coniferous trees accounting for ≥ 75% of total basal area.	25,748,365
Mixedwood forest	Mixedwood Dense, Mixedwood Open, Mixedwood Sparse	Predominantly forested areas with crown closure ≥ 10% and neither deciduous nor coniferous trees accounting for ≥ 75% of total basal area.	1,103,831
Shrub	Shrub tall, Shrub low, Prostrate dwarf shrub	At least 20% ground cover which is at least one-third shrub.	2,542,251
Bryoids	Bryoids	At least 20% ground cover or 33% total vegetation is bryophyte (mosses, liverworts, hornworts) or lichen	2,819
Herbaceous	Tussock graminoid tundra, Wet sedge, Moist to dry non-tussock graminoid/dwarf shrub tundra, Dry graminoid prostrate dwarf shrub tundra	Minimum of 20% ground cover or one-third of total vegetation is vascular pland without woody stem.	1,727,170

Treed peatland	Wetland – Treed	Peatland where majority of vegetation is tree.	8,441,670
Shrub peatland	Wetland – Shrub	Peatland where majority of vegetation is shrub.	5,034,885
Herbaceous peatland	Wetland – Herb	Peatland where majority of vegetation is herbaceous.	1,145,984
Barren	Snow/ice, Rock/rubble, Exposed land, Sparsely vegetated bedrock, Sparsely vegetated till-colluvium, Bare soil with cryptogam crust – frost boils	Predominately non-vegetated	302,390
Lake	Water	Lentic systems	3,471,470
River	Water	Lotic systems	522,032
Annual cropland	Annual cropland	Annually cultivated cropland	1,978,134
Forage cropland	Perennial cropland and pasture	Periodically cultivated cropland.	2,284,233

The GeoBase dataset does not include forest age information. Time since disturbance (see Appendix 6.1 for a summary of forage age data) was added to the land cover data using a map of forest stand age created by Chen et al. (2003) from the Canadian Forest Inventory, fire polygon data, and remote sensing. The forest stand age map has a resolution of 1 km^2 and was current to 1998.

1.1 Footprint

The abundance and location of 12 footprint types were derived from a variety of footprint inventories (Table 2). Where possible, inventories with coverage across the study area were used. Exceptions were pipeline and seismic inventories, for which provincial data sets were used where possible due to the incompleteness of the national (i.e., CanVec) inventory which has not been updated since the mid 1990's. For seismic, a provincial inventory was only available for British Columbia. For the remaining jurisdictions, the CanVec inventory was corrected so that seismic density was comparable to that estimated using more current inventories available for subsets of the study area[1]. When integrating the footprint inventories, footprints occasionally overlapped. To avoid double counting anthropogenic disturbance, overlapping footprints were assigned to a single footprint type, with more permanent footprints such as settlements or roads taking precedence over temporary footprints such as seismic lines and well sites. The proportion of each footprint's total area that was excluded due to overlap with

[1] In Alberta, CanVec seismic density was increased to be consistent with seismic density calculated from the provincial Base Features Database (updated to 2006), as reported by Schneider et al. (2010) for caribou herd ranges in the province. CanVec seismic density was 35% relative to Base Features. Therefore, a 2.89 correction factor was applied to the CanVec seismic inventory in Alberta.
The 2.89 correction factor was also applied to the CanVec seismic inventory in Saskatchewan. This may be an underestimate, given that seismic density calculated from CanVec (8.9e-03 km/km^2) was only 9% of that calculated from updated data (1.01e-01 km/km^2; Peter Lee, pers. comm.) for the Smoothstone Wapawekka caribou range in central Saskatchewan, to the east of the study area boundary.
In the Northwest Territories, the correction factor for seismic (1.43) was based on a comparison of seismic density calculated from CanVec (0.459 km/km^2) to that calculated from a 2005 inventory (0.656 km/km^2) for the southern Dehcho Territory (Carlson et al. 2007).

other footprints was calculated[2], and were applied in simulations to reduce footprint growth rates to account for overlap with other features.

Most footprint inventories existed as line or point data, requiring that assumptions be made for the widths of footprints so that areas could be computed. Widths of linear footprints were as follows (ALCES Group 2011): major road = 40 m, minor road = 24 m, transmission line = 40 m, seismic lines = 4.5 m, pipelines = 15 m. Widths of polygon footprints, based on Wilson et al. 2008, were as follows: gravel pit = 300 m, industrial plant = 500 m, rural residential/camp = 100 m, wellsite = 100 m, oil sands pit = 1000 m.

Table 2. Area and length by footprint type, and data sources used.

Footprint type	Data source	Area (ha)	Length (km)
Major road	GeoBase national road network[3]	179,382	70,929
Minor road	GeoBase national road network	39,324	16,385
Railroad	CanVec	7,140	3,570
Transmission corridor	CanVec[4]; entities = power transmission line, transmission line	17,709	4,427
Pipeline	Provincial inventories	229,091	152,727
Seismic	Provincial inventory for BC. Corrected CanVec inventory for AB, SK, and NT	430,745	957,211
Wellsite	GFWC national well data set	139,546	57,529
Industrial plant	CanVec (entity = gas and oil facilities) and provincial inventories	56,527	14,757
Oilsands mine	Oil sands surface mining activity in Alberta, Canada up to 2008 (GFWC, provided through databasin)	64,951	785
Gravel pits	CanVec (entities = extraction area, pit)	3,852	775
Settlements	CanVec (entities = residential area)	44,616	1,119
Rural residential	CanVec (entity = building, camp)	60,608	23,481

The resulting land cover and footprint baseline layer is shown in figure 3. Scenarios modelling in ALCES used this initial state to model landscape changes over time under different development rates and management practices.

---

[2] The proportion of each footprint's area that is excluded due to overlap with other footprints was: road=3.5%; railroad=7.0%; transmission line=7.2%; pipeline=8.4%; seismic=2.6%; wellsite=7.0%; industrial plant=1.4%; oilsands mine=0.3%; gravel pit=6.2%; rural residential=12.1%; and settlement=0%.

[3] The Geobase national road network, released in 2007, represents the centerline of all non-restricted use roads in Canada (≥ 5 m wide, drivable, and with no barriers denying access). Some resource and recreational roads may not be included in the data set (Centre for Topographic Information 2007a). The minor road footprint type refers to resource/recreational road types from the national road network (Centre for Topographic Information 2007b). All other road types from the national road network are included in the major road footprint type.

[4] The Canvec data product, produced by Natural Resources Canada, is a multi-source product that aims to provide a standardized representation of topographical phenomenon for all of Canada (Centre for Topographic Information 2010a). CanVec is updated twice annually. A subset of CanVec's more than 90 topographical entities (Centre for Topographic Information 2010b) was used to derive the locations of various footprint types in the study area.

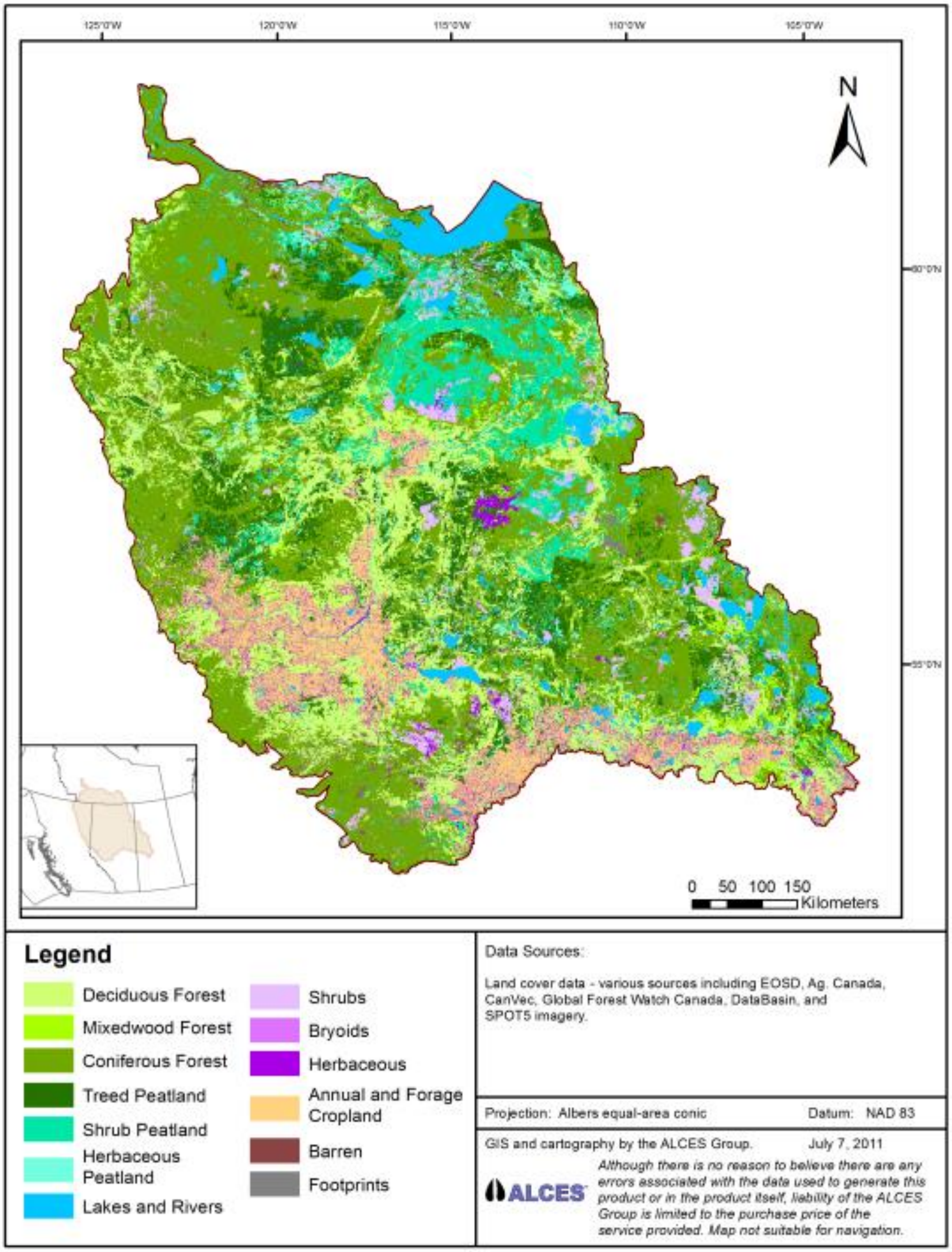


Figure 1. Initial composition of the study area.

2 Ecological Processes

2.1 Fire

Fire, the dominant natural disturbance in the study area, has a large influence on the composition of boreal landscapes. The annual area burned in the region is highly variable, making it difficult to identify a typical burn rate. From 1959 to 1999, the average burn rate in the region was 0.60%[5]. However, estimates of the typical burn rate in the region are varied, and include (among others) 0.4% per year (Cumming 1997), 1.25% per year (Wilson et al. 2008), and 2.2% per year (Murphy 1985). Contributing to the diversity of fire rate estimates for the region is the highly variable nature of the fire regime (Armstrong 1999). The annual area burned in the Boreal Plains fluctuated dramatically between 1959 and 1999, with almost half of the total burn area occurring during just 3 years (1980, 1981, and 1995). Further complicating the issue is that warmer temperatures due to climate change are expected to increase the rate of fire in the region. One study estimated that the burn rate may double by mid-century and increase by as much as 5.5 times by the end of the century (Balshi et al. 2009).

2.1.1 Fire Simulation in Land Use Scenarios

Fire was included in land use simulations to incorporate its effect to forest age and related indicators such as wildlife, carbon, and timber production. Although the fire regime is temporally variable, it was simulated deterministically during land use scenarios to avoid obscuring differences in simulation outcomes that are attributable to land use. As per Schneider et al. (2003), a 1% per year burn rate was adopted in the simulations. The rate was applied across forest types (i.e., deciduous, coniferous, mixedwood). Although some studies in the region have demonstrated differences in burn rates between cover types, the results are not consistent. For example, using a reconstruction of the historical fire regime in Wood Buffalo National Park, Larsen (1994) calculated a burn rate for aspen that was approximately twice as high as that for spruce. In contrast, Cumming (2001) concluded that the fire rate of deciduous forest was lower than that of coniferous forest by as much as an order of magnitude in the Alberta-Pacific Forest Management Agreement area (Al-Pac FMA) in northeastern Alberta. Applying the burn rate equally across cover types is supported by average forest age estimates that are approximately equal across forest types (82, 84, and 80 years for coniferous, deciduous, and mixedwood forest, respectively).

Land use simulations also assumed an equal burn rate spatially across ecoregions. Although the large fire database exhibits variability in burn rate across ecoregions (0.12% to 2.52%), the variability may be an artefact of the short time series and the small size of ecoregions relative to the spatial scale of the fire regime (Stocks et al. 2002). Infrequent but large fire years have the capacity to burn much of the forest within an ecoregion, and such an event can have a dominating influence on average ecoregional burn rates during the LFDB’s 40 year period. For example, although the Slave River Lowland ecoregion exhibited the highest average burn rate, 71% of ecoregion’s burn area between 1959 and 1999 occurred during just two years (1980 and 1981).

---

[5] The average burn rate was calculated from the Canadian Forest Service’s large fire database (LFDB) which includes information on fires in Canada between 1959 and 1999 (Stocks et al. 2002). Although the dataset is limited to fires larger than 200 ha, it accounts for 97% of the total area burned (Stocks et al. 2002).

The simulated spatial distribution of fire (i.e., fire size) was based on the size distribution of fires in the region from 1959 to 1999 according to the Canadian Forest Service's large fire database.

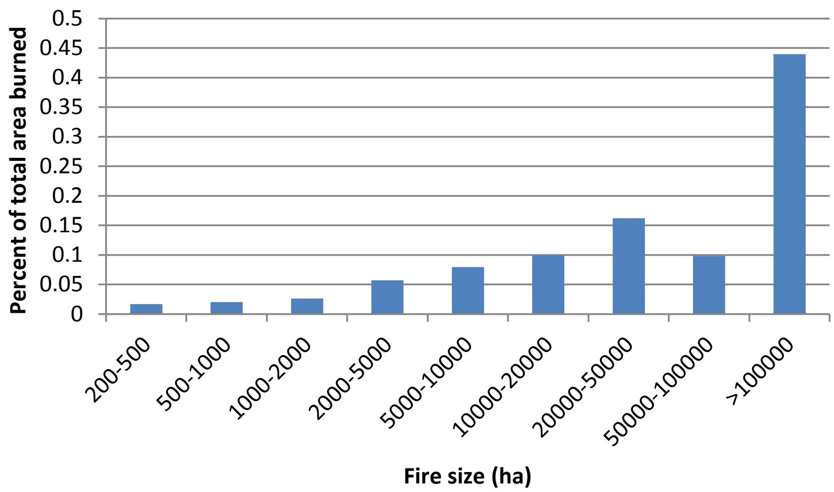


Figure 2. Distribution of area burned across fire size classes in the Boreal Plains ecoregion between 1959 and 1997 (Stocks et al. 2002).

2.1.2 Fire Simulation in Range of Natural Variability Estimation

To estimate the range of natural variability for ecological indicators, fire was simulated in the absence of land use. A natural fire rate of 1.1% was assumed, based on Armstrong (1999). The 1.10% annual fire rate estimate is less than some estimates for the region[6] and exceeds others[7].

The fire rate was simulated as a stochastic process when estimating the natural range of variability in order to approximate the effect of a variable fire regime on forest age and related indicators. The stochastic fire regime was simulated as random draws from a lognormal distribution, a distribution well suited for characterizing highly variable fire regimes (Armstrong 1999) such as that of the Boreal Plains. The standard deviation of the lognormal distribution was 1.741, the standard deviation across the lognormally transformed annual burn areas for the study area (based on LFDB). When simulating burn rates for northeastern Alberta, Armstrong (1999) truncated the lognormal distribution by assuming that no more than 100% of the study area could burn in any year. Here, a maximum fire rate of 10% was used based on an assumption that it is unlikely that more than 10% (32,000 km^2) of the study area's forest would burn in any year. Between 1959 and 1999, the largest percent of the forested portion of the study area that burned in a single year was 7.4%[8]. A moderately higher burn rate than 7.4% may be possible in the absence of fire suppression. An implication of imposing a maximum fire rate is that the

[6] Annual burn rate estimates that exceed 1.1% include Larsen's (1994) 1.6% estimate for Wood Buffalo National Park and Van Wagner's (1978) 2% estimate for west-central Alberta

[7] Annual burn rate estimates that are less than 1.1% include Cumming's (2001) 0.21% estimate for the Al-Pac FMA.

[8] Higher single year burn rates have been estimated for Wood Buffalo National Park (Larsen 1994). However, the small sizes of that landscape relative to the size of this project's study area is such that single large fires can cause very high burn years. Such extreme rates of burn are unlikely across a 700,000 km^2 region.

average simulated fire rate under-represents the mean of the distribution prior to truncation (Armstrong 1999). To ensure that the simulations, on average, approximate estimates of presuppression fire rates, the mean of the lognormal distribution was inflated to 1.4% to account for the truncation[9].

Visual comparison of the truncated lognormal distribution with the LFDB Boreal Plains data demonstrate that the lognormal distribution successfully represents the fire regime's pattern of typically low fire years punctuated by infrequent large fire years (Figure 3). The more frequent and extreme large fire years simulated by the lognormal distribution are as expected given that the average fire rate is approximately double that of the LFDB time series.

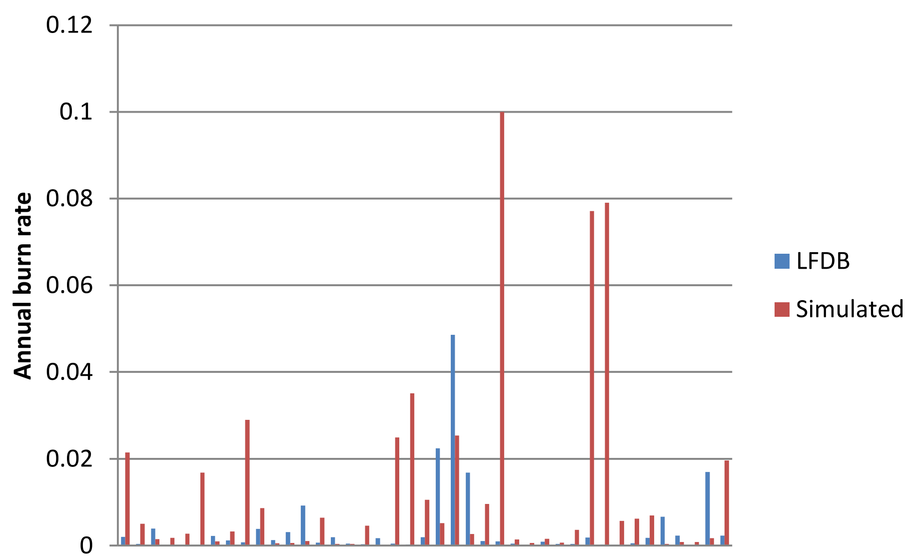


Figure 3. Percent annual area burned for a) the Boreal Plains ecozone between 1959 and 1997 from the Large Fire Database (LFDB), and b) the first 39 of 10000 random numbers generated from a lognormal distribution truncated at 10% with a post-truncation annual mean rate of 1.1%.

Fire was assumed to be stand replacing, therefore fire affected forest age-class structure but not cover type. Fire did not affect the lifespan of anthropogenic footprints, with the exception of seismic lines which were removed by fire.

2.2 Succession and Growth and Yield

Forests accumulated and lost biomass with age according to growth and yield curves developed for the Al-Pac Forest Management Agreement (FMA), large forest tenure (approximately 60,000 km^2) located in northeastern Alberta. Growth and yield curves for each of the deciduous, coniferous, and mixedwood

---

[9]A simulation experiment was conducted to explore the consequences of truncating lognormal distributions at 0.1 (i.e., 10%). Ten thousand random numbers were generated from each of ten lognormal distributions with means ranging from 0.001 to 0.02 (on the original scale). For each distribution, the mean across the 10,000 generated numbers was calculated and compared to the target burn rate of 0.011. A lognormal distribution with a pre-truncation mean of 0.014 generated a post-truncation mean of 0.011 and will therefore be used in the natural range of variation simulations.

forest types (Appendix 6.2) were estimated as area-weighted averages of yield curves reported in the Al-Pac detailed forest management plan (DFMP; Al-Pac 2008). Given the large size of the study area, growth and yield (i.e., forest productivity) is likely to vary across the region. To assess whether the Al-Pac yield curves overestimate the productivity of more northern portions of the study area, forest productivity within the Al-Pac FMA area was compared to forest productivity within the Tolko High Level FMA area (Tolko High Level Lumber Division and Footner Forest Products Ltd. 2003). Tolko High Level is one of the most northern FMA areas within the study area (extending to the AB/NWT border because FMA's do not exist within the NWT), and is predominantly within the Taiga Plains ecozone. Productivity was assessed by comparing mean annual increment (m^3/ha/year) at forest age 100 (Table 3). Forest productivity was judged sufficiently similar to permit the application of a single set of yield curves (i.e., from the Al-Pac FMA area) for the entire study area.

Land cover types did not change during succession and disturbed vegetation returned to its pre-disturbance cover type with an age of zero following fire, timber harvest, or footprint reclamation.

Table 3. Mean annual increment (m^3/ha/year) at forest age 100 for the Al-Pac and Tolko High level Forest Management Agreement areas.

	Deciduous	**White spruce**	**Black spruce**	**Mixedwood**
Al-Pac	2.5	2.4	1.1	2.4
Tolko High Level	2.4	2.3	1.1	2.2

3 Land-use Scenarios

The scenario analysis did not attempt to predict the future, but rather present a suite of plausible futures that demonstrate logical outcomes of alternative land-use options. The scenarios were selected to assess the strategic benefits and liabilities of land use in the western boreal region, and options for balancing development with conservation. More specifically, the suite of scenarios assessed the implications of manipulating development rates, management practices, and zoning for the five main land uses in the region (oil and gas, forestry, agriculture, settlements, and transportation). Settings for development rate, management practices, and conservation zoning are summarized below.

1. Development rate. Three development rates were simulated: low, moderate, and high. The three development rates reflected: reduced or stagnant commodity prices, moderate commodity prices, and robust and sustained commodity prices.

2. Management practices. The effectiveness of best practices was explored, whereby best practices refer to strategies to minimize the impact of resource development without affecting the rate of commodity production.

3. Conservation zoning: a suite of scenarios explored the consequences of zoning portions of the landscape for wildlife conservation. It was assumed that the pace of land use outside of protected areas would not intensify to offset the reduction in development caused by protection.

Accurate forecasting is problematic because uncertain factors such as societal values, government policy, global commodity prices, and technological innovation all affect future land use. However, examining plausible futures using transparent assumptions based on best-available information allows potential benefits and impacts to be understood and evaluated today to identify risks and uncertainties. When faced with uncertainty, we attempted to derive conservative assumptions for the rate of future development and the intensity of associated footprint, so as not to exaggerate future disturbance that can be expected in the region (Table 4). Furthermore, the evaluation of three levels of development (low, moderate, and high) permits the assessment and projected implications of a range of development rates to future indicator condition.

Table 4. Examples of conservative assumptions for the oil and gas and forestry sectors, the two major land uses in the region.

Sector	Examples of conservative assumptions
Hydrocarbon development	• Not including oil shale and coal bed methane development, both of which are intensive with respect to footprint. • Assuming high productivity for insitu and shale gas wells, such that footprint per m^3 of production declines as production shifts from conventional to unconventional hydrocarbons. • Not increasing overall gas production (i.e. conventional plus unconventional) from the region over the simulation period.
Forestry	• Not simulating regeneration delay or shifts in species composition after timber harvest.

	• Salvaging all merchantable timber from forest cleared for industrial development. • Not simulating a decline in growth and yield for northern portions of the study area. • Not including insect-related forest mortality
Agriculture	• Simulated rate of expansion in agricultural land was lower than the historical rate of expansion
Settlements	• The simulated population growth rate was substantially lower than the long-term historical population growth rates of the study area's two most populous municipalities (Fort McMurray and Grande Prairie)

Land-use assumptions are now described in greater detail.

3.1 Oil and Gas

3.1.1 Conventional Oil and Gas

Conventional production of oil and gas in the Western Canadian Sedimentary Basin is declining due to the maturing status of most hydrocarbon fields (National Energy Board; NEB 2003). To develop conventional oil and gas production and drilling trajectories for the study area, declining production projections for Alberta for 2012-2021 (Energy Resource Conservation Board; ERCB 2012) were extrapolated to 2062, and then adjusted for based on conventional oil and gas remaining established reserves in the study area relative to Alberta. The Alberta projection was used as the basis for the production trajectory because it was the best information available and because Alberta contains the majority of conventional oil and gas reserves in the basin (Mossop and Shetsen 1994).

Conventional oil and gas production in the low and high scenarios was ±20% of the moderate scenario for consistency with assumptions for the bitumen trajectories.

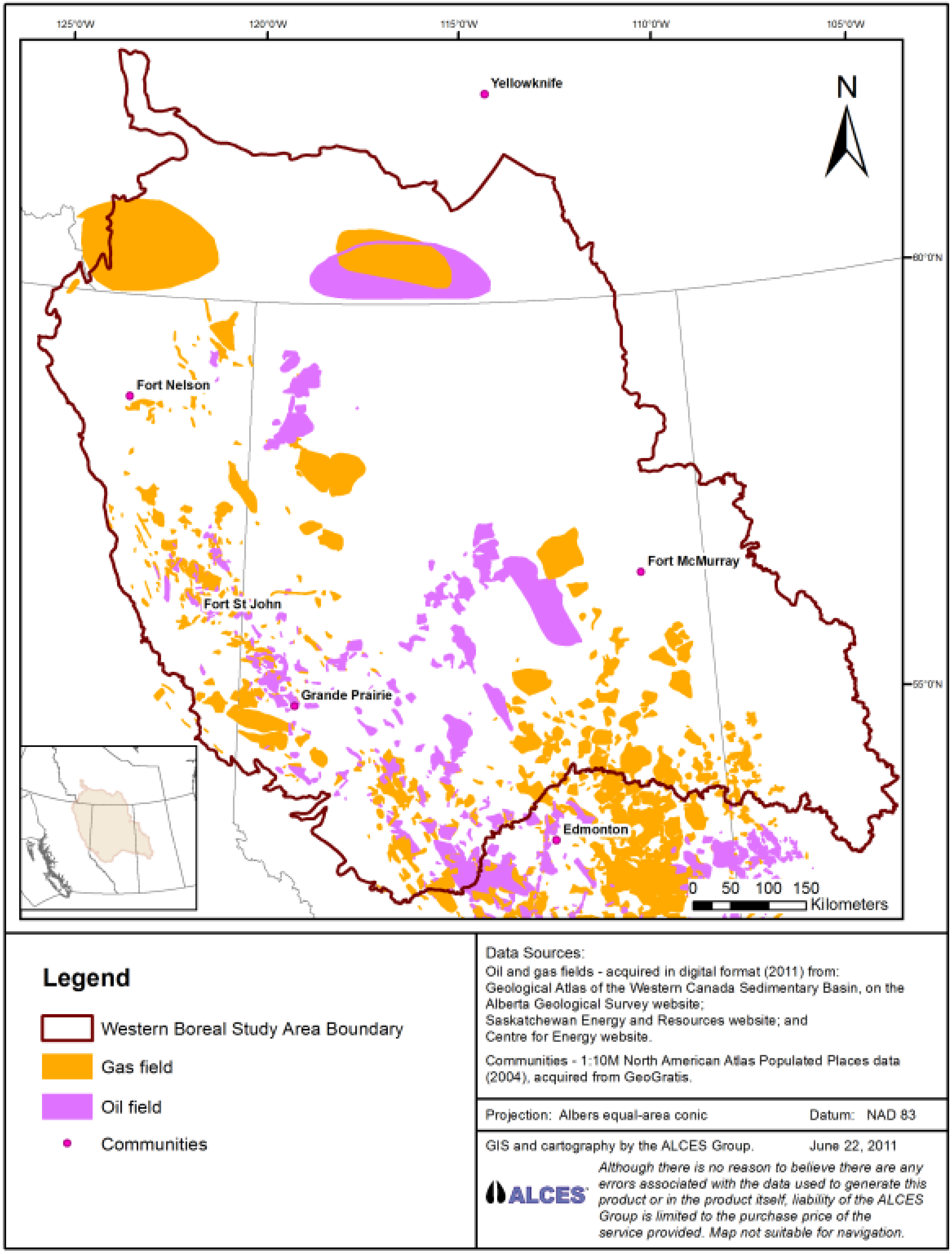


Figure 4. Conventional oil and gas fields within the study area.

3.1.1.1 Conventional Oil

Energy Resources Conservation Board (2012) projects conventional oil drilling in Alberta to decline from 3600 wells in 2012 to 2600 by 2021. The average annual decline in drilling rate (125 wells/year) over this period was carried forward, resulting in cessation of drilling by 2041.

The productive lifespan of wells was simulated at 20 years, based on a comparison of historical trajectories for completed and active wells in Alberta. For example, the number of conventional oil wells completed in the past 20 years (41,716 (Canadian Association of Petroleum Producers; CAPP 2012) is similar to the number of wells that are active today (37,697; ERCB 2012). Initial well productivity was the average productivity of conventional oil wells in 2011 (2 m^3/day/well; ERCB 2012). As expected for a maturing resource, productivity has declined from 23 m^3/day in 1973 to 5.5 m^3/day in 1991 and 2.0 m^3/day in 2011. The decline in productivity from 1991 to 2011 was approximately 5% per year. The future rate of decline in productivity is assumed to be 2.5%/year. The assumed rate of decline is lower than what occurred over the past 20 years to reflect increased adoption of more productive horizontal drilling. When combined with the drilling trajectory and 20-year lifespan assumption, a 2.5% annual decline in productivity projects conventional oil production of 26.4 million m^3 in 2021, which is similar to that projected by ERCB (26.0 million m^3).

Conventional oil production and drilling trajectories for the study area were derived by reducing the provincial trajectory in proportion to the availability of conventional oil remaining established reserves. Remaining established reserves in the Alberta/British Columbian portions of the study area were estimated using the Geological Atlas of the Western Canada Sedimentary Basin (Mossop and Shetsen 1994). The Atlas provides remaining reserve estimates for conventional oil in the basin, as well as shape files of the deposits. Remaining reserve estimates for Alberta and the study area were estimated based on the extent to which they included oil deposits associated with each stratigraphic interval. For Saskatchewan, remaining established reserves (300,374 m^3) were from Saskatchewan Ministry of Energy and Resources. All boundaries of oil and gas deposit polygons were downloaded from the Government of Saskatchewan's Oil and Gas InfoMap. For the Northwest Territories, the remaining established reserve estimate was that provided by Drummond (2009) for the Southern Northwest Territories, NWT (413,366 m^3). The resulting reserve estimate for the study area was 56.1% of that for the province of Alberta. Therefore, Alberta projections for conventional oil production and drilling were reduced by 43.9% to derive projections for the study area.

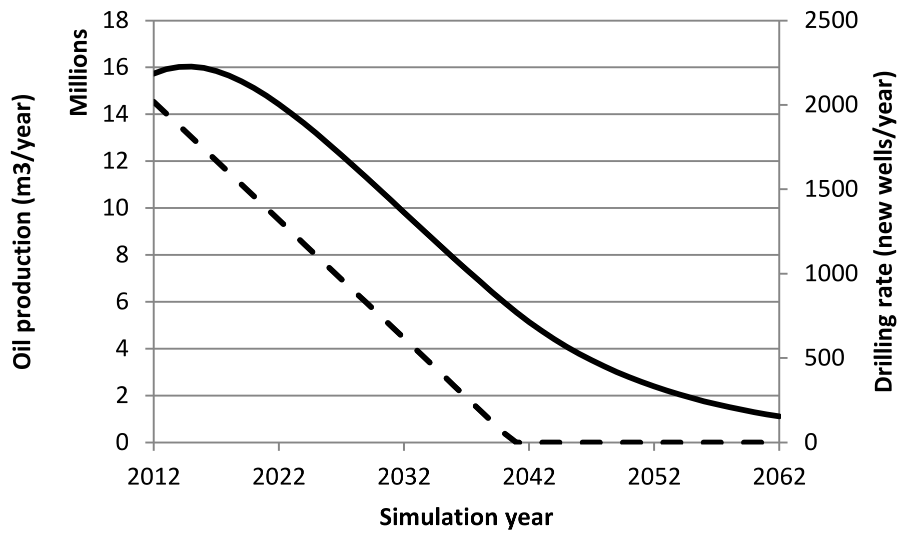


Figure 5. Conventional oil production (solid line) and drilling (dashed line) trajectories for the moderate development scenario.

3.1.1.2 Conventional Gas

The Energy Resources Conservation Board natural gas projection is based on two sets of assumptions, one for southeastern Alberta where productivity is low and the other for the remainder of the province. When extrapolating the ERCB projection, production from southeastern Alberta was excluded because the high level of drilling and low productivity per well in that region is not representative of production in the remainder of the province. Not including southeastern Alberta, ERCB expects drilling to increase from 972 wells per year in 2012 to 2280 wells per year in 2280. Beyond 2021, it seems unlikely that the upward trend will continue given the maturing state of the resource. The National Energy Board (2011a) projects the rate of drilling to decline by 7% between 2021 and 2035. This was reflected in the simulations by reducing the drilling rate by 20 wells/year for the period of 2022 to 2062.

The productive lifespan of wells was simulated at 15 years, based on a comparison of historical trajectories for completed and active wells in Alberta. For example, the number of gas wells completed in the past 15 years (106,510; CAPP 2012) is similar to the number of wells that are active today (111,120; ERCB 2012). Initial well productivity was the average productivity of conventional gas wells in 2011 for Alberta, excluding the southeast (1.948 million m^3/well/year; ERCB 2012). The ERCB's (2012) projected production curve assumes declining production from existing wells, resulting in a decline in total annual production of 32% from 2011 to 2021. A 1.5% annual decline in well productivity was simulated because, when combined with the drilling trajectory and 15 year active lifespan assumptions, it produced the same decline in total production from 2011 to 2021 as exhibited by ERCB's (2012) projection.

As for conventional oil, the Alberta conventional natural gas trajectory was adjusted based on the availability of reserves in the study area relative to Alberta (excluding southeastern Alberta). Remaining reserve estimates for Alberta and the Alberta/British Columbia portion of the study area were estimated from Mossop and Shetsen (1994) based on the extent to which they included natural gas deposits associated with each stratigraphic interval. For Saskatchewan, remaining established reserves (1.38

billion m^3) were from Saskatchewan Ministry of Energy and Resources. All boundaries of oil and gas deposit polygons were downloaded from the Government of Saskatchewan's Oil and Gas InfoMap. For the Northwest Territories, the reserve estimate was the remaining discovered gas resource estimates provided by Drummond (2009) for the Liard Plateau (2.61 billion m^3) and Southern Northwest Territories (2.54 billion m^3). The resulting reserve estimate for the study area was 65.2% that of the Alberta (excluding southeastern Alberta). Therefore, provincial projections for conventional natural gas production and drilling were reduced by 34.8% to derive projections for the study area.

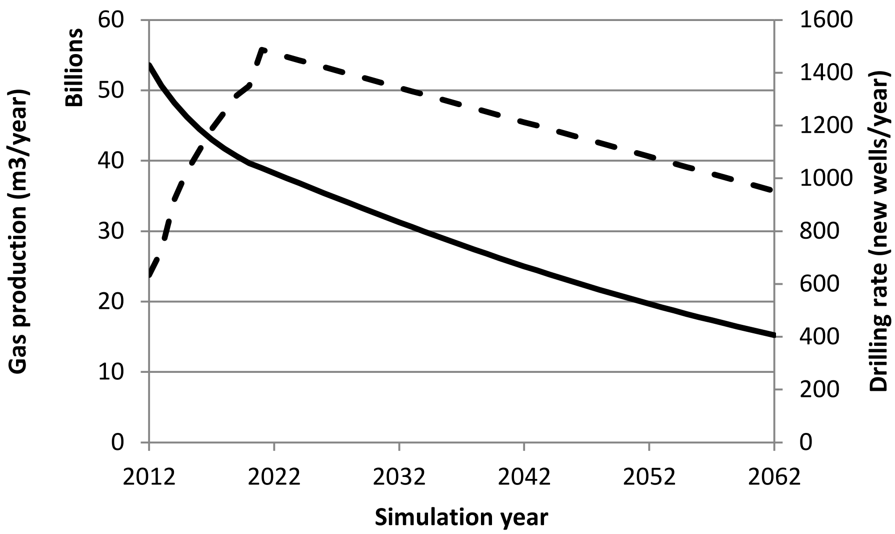


Figure 6. Conventional natural gas production (solid line) and well drilling (dashed line) trajectories for the moderate development scenario.

3.1.2 Unconventional Oil and Gas

The primary unconventional hydrocarbons in the study area are bitumen (mineable and in-situ) and shale gas. Coal bed methane also occurs in the far southern portion of the study area, but is not included in the scenario analysis because reserves are small relative to shale gas. Although very abundant within the study area, oil shale is also not considered in this study because its development is still sufficiently prospective to preclude parameterization of development trajectories and footprint.

3.1.2.1 Shale Gas

The three major shale gas deposits overlapping the study area are the Horn River Basin. The estimated Gas in Place (GIP) = 12,629 billion m^3) [10], Montney Formation (GIP = 11,035 billion m^3) [11], and Colorado Group (GIP = 2,800 billion m^3) [12]. Approximately 20% of the GIP may be recoverable (NEB 2009)[13]. Development of shale gas is in its early stages[14], and information on the future rate of development is

---

[10] Estimate of gas in place is from BC Ministry of Energy and Mines and NEB (2011).

[11] Estimate of gas in place is the average of low and high estimates from BC Ministry of Energy and Mines and NEB (2011).

[12] Estimate of gas in place is the average of low and high estimates from NEB (2009).

[13] To date, ultimate potential has only been estimated for the Horn River Basin. The estimated ultimate potential (2,198 billion m^3) is 17.4% of the estimated gas in place (12,629 billion m^3).

[14] In 2010 there were 250 shale gas connections in Alberta (ERCB 2010), all of which are likely associated with vertical wells. In 2009, there were 234 production wells in the Montney formation and 20 wells in the Horn

limited. However, increased shale gas production is expected to reverse declines in conventional gas production from the Western Canadian Sedimentary Basin over the next decade (Natural Resources Canada 2008, Collyer 2010). In BC, where the Horn and Montney deposits occur within the study area, TransCanada pipelines is expecting shale gas production to increase to more than 5 billion cubic feet/day (~52 billion m^3/year) by the end of the decade (TransCanada 2011); this level of production is similar to current conventional natural gas production in the study area.

In the absence of more detailed information, the moderate land-use scenario assumed that shale gas production in the study area increased to approximately offset the decline in conventional natural gas production. For instance, the combined production of conventional and shale gas remained relatively constant during the moderate scenario. Expansion rates of 400 horizontal wells and 50 vertical wells[15] per year were sufficient to return gas production to current rates by a couple of decades into the future (Figure 8). The assumption is consistent with expectations that shale gas will reverse the declining trend in gas production in the Western Canadian Sedimentary Basin, and may be conservative given that demand for natural gas in Alberta is expected to increase substantially due to the energy requirements of oil sands production (ERCB 2010). Shale gas production in the low and high scenarios was ±20% of the moderate scenario for consistency with assumptions for the bitumen trajectories.

Well production varies markedly depending on whether horizontal or vertical drilling is applied. The two expected ultimate resource estimates reported in northeastern British Columbia in 2012 were 3.4 and 7.0 billion cubic feet of gross production per well. Assuming that approximately 83% of the production will be marketable (ERCB 2009) and assuming a 30 year lifespan (Alexander et al. 2011, Hayden and Pursell 2005), a reasonable estimate of average annual production from a horizontal well in the region is 4 million m^3 per well. In contrast, average production per well from vertical shale gas wells in Alberta in 2011 was 639 thousand m^3/year (ERCB 2010) [16]. Due to their higher productivity, and despite their substantially higher cost, simulations assumed that horizontal wells were used, with the exception of the Colorado deposit due to unfavourable rock conditions (NEB 2009). Future horizontal wells were distributed between the Horn River Basin and Montney Formation relative to their GIP estimates (Table 5).

---

formation (NEB 2009). Drilling in 2011 was expected to add over 300 connections in the Montney and Horn formations (NEB 2011, Appendix B), suggesting that at least 500 production wells may have been added in the Montney and Horn formations of BC since 2009, for a total of approximately 750.

[15] The ratio of horizontal to vertical well drilling is based on the current distribution of shale gas wells. In northeastern British Columbia, where horizontal drilling is typically used, there are 1000 wells (British Columbia Ministry of Energy and Mines 2012). In Alberta, where vertical drilling has been more prominent, there are 149 wells (ERCB 2012).

[16] 324 thousand m^3/year likely overestimates average annual production from a vertical shale gas well because it reflects production from young wells. Production from shale gas wells drops rapidly from initial production rates; well production in the Barnett Shale deposit was found to decline by more than 95% in the first 5 years (Hayden and Pursell 2005).

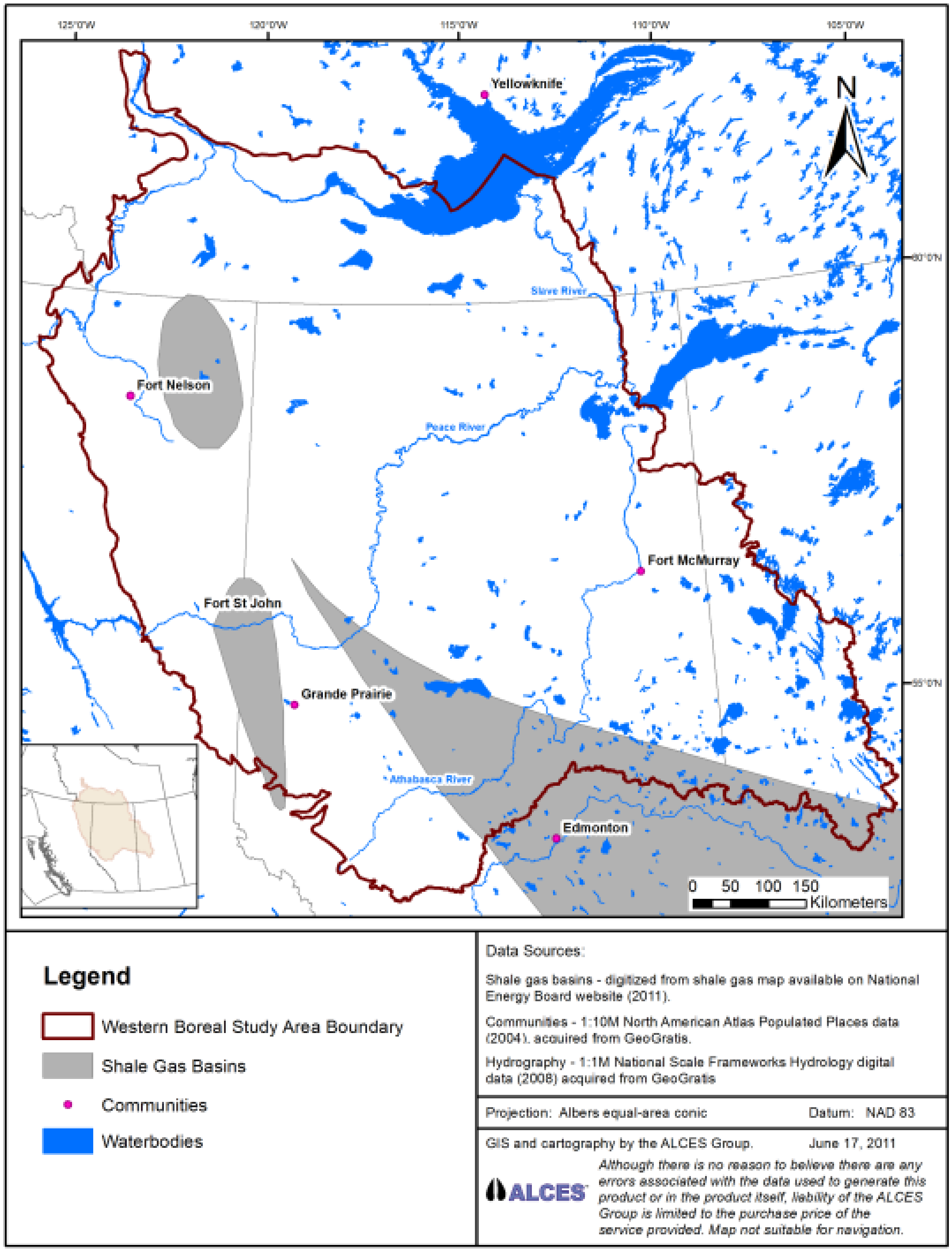


Figure 7. Shale gas basins within the study area.

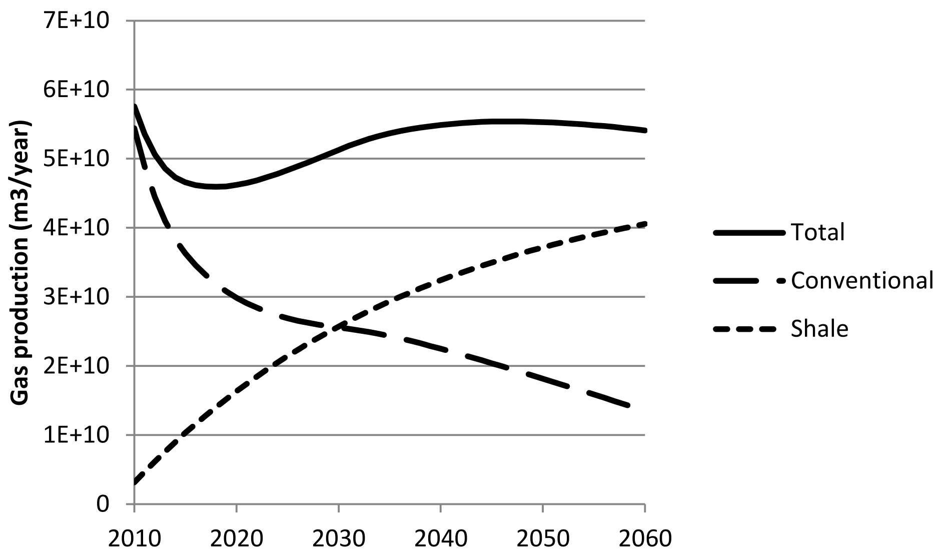


Figure 8. Conventional and shale gas production for the moderate development scenario.

Table 5. Estimated shale gas in place (GIP) for basins overlapping with the study area. Study area GIP estimated for total basin GIP based on the proportion of the basin area that is within the study area.

Basin	**Basin GIP (billion m^3)**	**% of basin within study area**	**Estimated study area GIP (billion m^3)**
Horn River	12,629	100	12,629
Montney	11,035	95	10,483
Colorado Group	2,800	15	420
Total	26,434		23,532

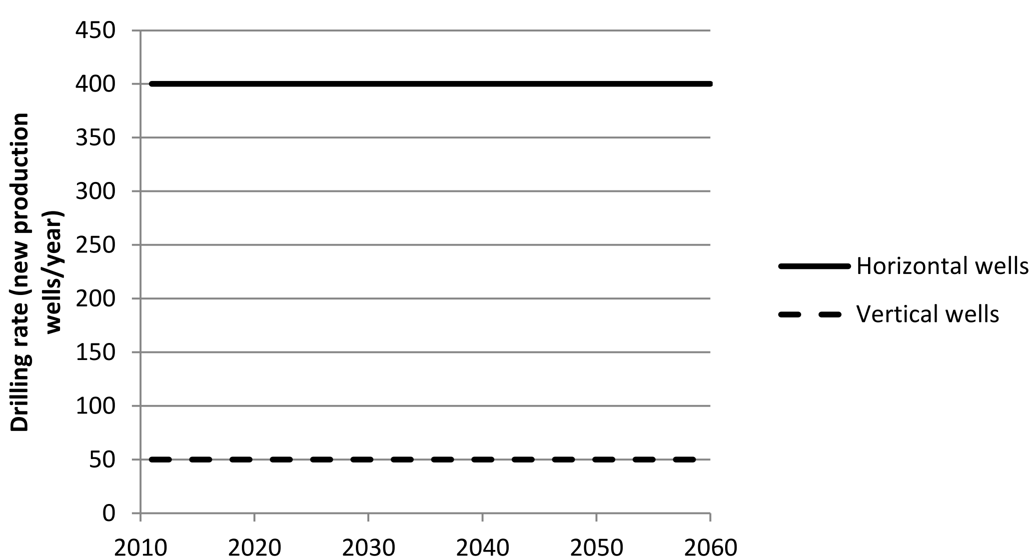


Figure 9. Drilling rate for horizontal and vertical shale gas wells in the moderate development scenario.

3.1.2.2 Bitumen

In contrast to conventional oil, bitumen production is expected to increase in the coming decades. The Canadian Energy Research Institute (CERI; Millington and Mei 2011) provide low ("protracted slowdown"), moderate ("realistic"), and high ("energy security") growth projections of oil sands development in Canada, all of which assume substantially increased production over the next 35 years. Each scenario has production increasing rapidly over the next two decades, and then continuing to increase but at a slower rate to reach 4.2, 5.1, and 5.8 million barrels per day (0.67, 0.81, 0.92 million m^3 per day) by year 2042 for the low, moderate, and high scenario, respectively. The bitumen production trajectories adopted for the simulations were based on the CERI projections, increasing rapidly at first and then levelling off towards the end of the 50-year simulation period at production levels similar to those associated with the protracted slowdown, realistic, and energy security scenarios (Figure 10). Under the moderate scenario, cumulative production over the 50-year simulation period was 12.5 billion m^3, which accounts for slightly more than one-third of the total extractable bitumen in the study area (Millington and Mei 2011). Cumulative production under the low and high scenarios is 80% and 120% of cumulative production under the moderate scenario, which is similar to the relative magnitude of the CERI scenarios. Production was distributed across oil sands areas relative to estimates of their initial volume in place[17]. All oil sands mining occurred within the mineable portion of the Athabasca oil sands area. In situ development was distributed as follows[18]; 80.3% within the Athabasca oil sands area, 10.8% within the Cold Lake oil sands area, 8.0% within the Peace River oil sands area, and 0.9% within the oil sands deposit in Saskatchewan.

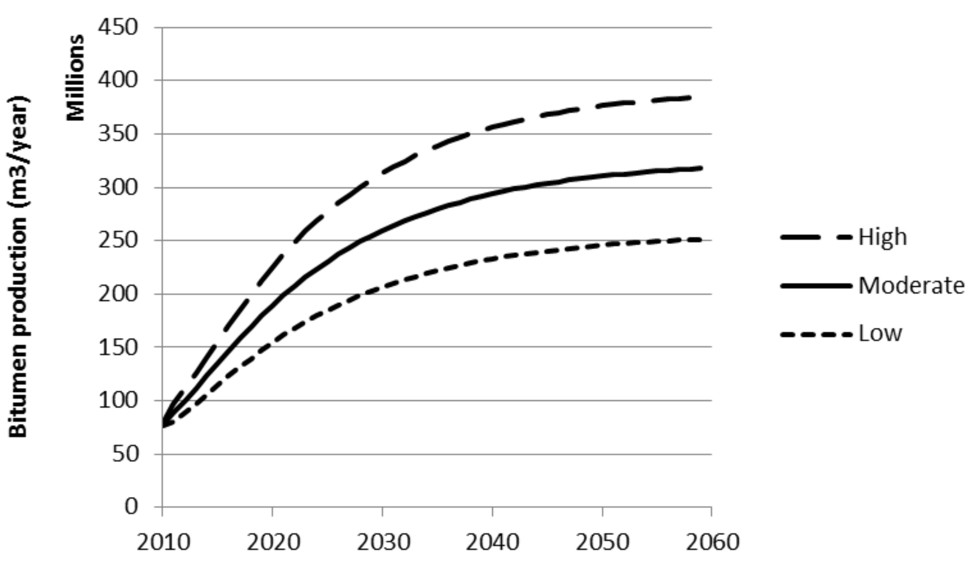


Figure 10. Bitumen production under low, moderate, and high development scenarios.

---

[17] Estimates of initial volume in place were used instead of estimates of recoverable volume were only available for areas under active development.

[18] ERCB's (2010; table 2.3) estimates of initial in situ volume in place are Athabasca=215,514 million m^3; Cold Lake=29,090 million m^3; and Peace River=21,560 million m^3. Initial volume in place for the Saskatchewan oil sands deposit is estimated at 2,355 million m^3 (derived from Prebble et al. 2009).

Although cumulative mineable bitumen production (718 million m^3) exceeds in-situ production (381 million m^3) to date, in-situ accounts for approximately 80% of the extractable reserves (Millington and Mei 2011). As such, in-situ production is expected to increase relative to mineable production, and eventually account for 80% of cumulative production. To divide future bitumen production between mineable and in-situ production, a sensitivity analysis was performed to approximate trajectories that obey initial conditions and follow Hubbert-Naill type curves that result in all recoverable mineable and insitu bitumen reserves being exhausted after 200 years. The resulting trajectories have in-situ production increasing more rapidly than mineable production, and accounting for 69% of cumulative bitumen production over the next 50 years (Figure 11). The mining rate (new ha/year) required to produce the moderate production trajectory was derived based on assumptions adopted by the Cumulative Effects Management Association (CEMA) to inform a scenario analysis exploring the future effects of land use in the Regional Municipality of Wood Buffalo in northeastern Alberta (Wilson et al. 2008), including an active mine lifespan of 20 years and productivity of 3,200 m^3/ha/year. The drilling rate (new production in-situ wells/year) required to generate the moderate production trajectory was derived by assuming an active well lifespan of 10 years (Wilson 2008). Average annual well productivity was initially at 2010 levels (~4000 m^3) and increased by 300 m^3 each simulation year thereafter to reflect increased use of steam-assisted gravity drainage. Steam-assisted gravity drainage (SAGD) production per well is substantially higher than that for CSS or primary, and productivity has increased by an average of 224 m^3 per year since 2004 due to the increasing prevalence of SAGD wells.

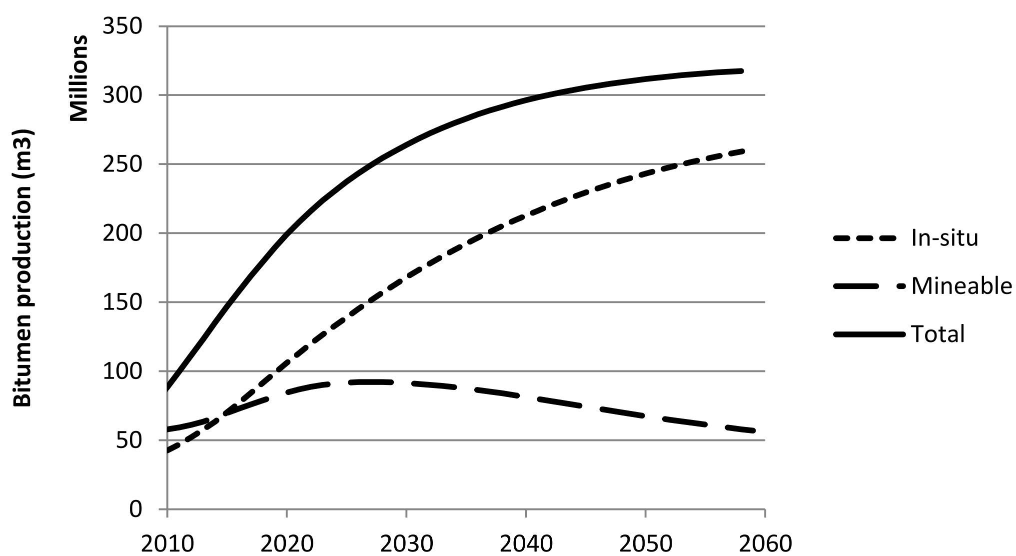


Figure 11. Annual bitumen production trajectories for the moderate development scenario.

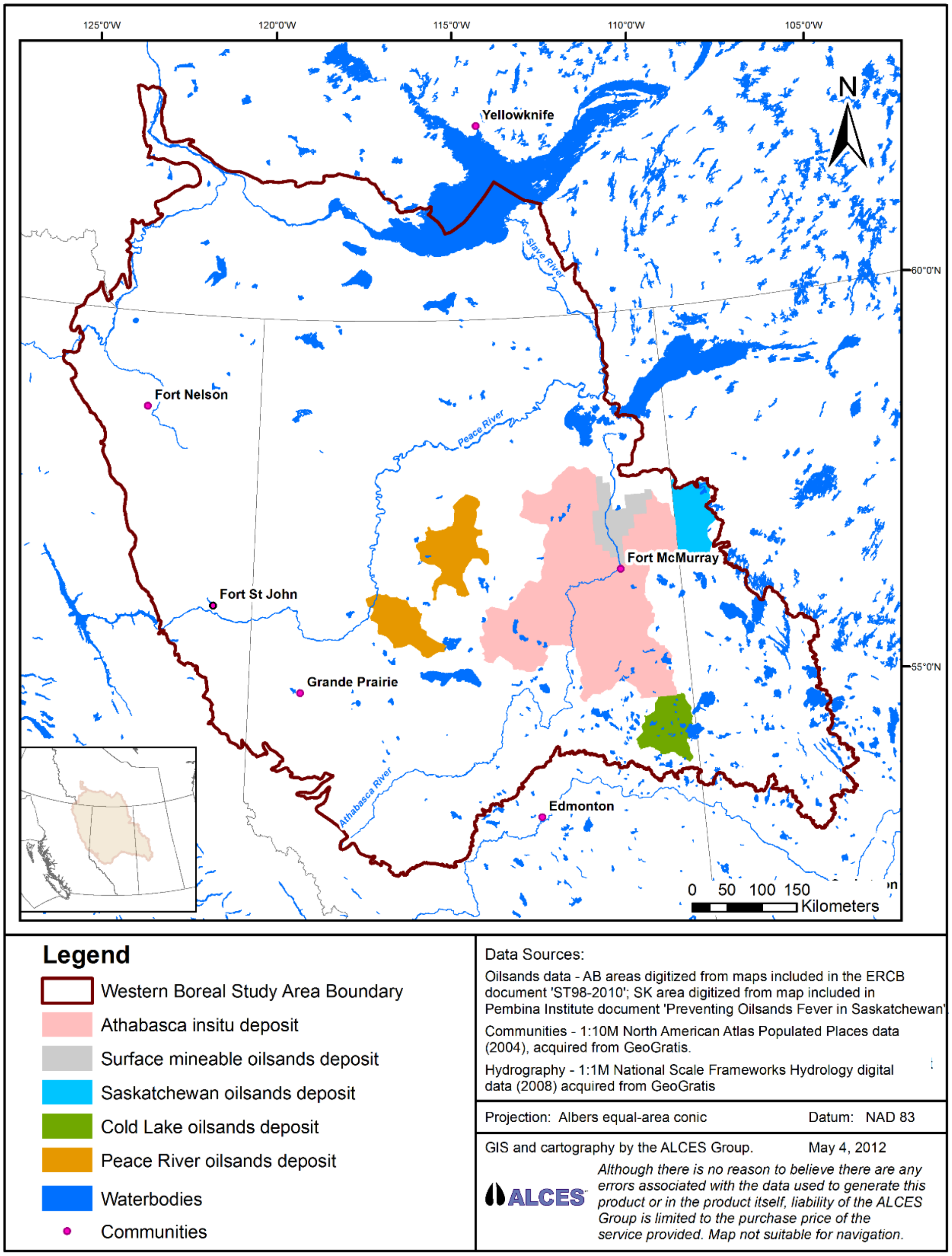


Figure 12. Oil sands deposits within the study area.

3.1.3 Hydrocarbon Footprint Intensity

Footprint intensity for bitumen production was based on assumptions adopted by CEMA to evaluate the cumulative effects of land use in a northeastern Alberta study area that accounts for much of the region's bitumen reserves (Wilson et al. 2008). Each new bitumen mine ha was associated with 1.3 ha of waste, tailings ponds, and facilities[19]. Each new in-situ bitumen well was accompanied by 0.62 km of pipeline, 7.7 km of seismic line, 0.53 delineation wells, and 0.2 ha of facilities[20]. Ten production wells occurred per 8.26 ha pad. Actual footprints associated with eight ongoing SAGD projects are relatively consistent with these footprint intensities (Hague and Wilson 2009)[21].

Footprint intensity for conventional oil and gas production was based on young to mature oil and gas plays in the foothills of Alberta (Terry Antoniuk, pers. comm.). Geospatial analyses of footprint determined that, on average, each producing or suspended well was associated with 0.5 abandoned wells (i.e., exploratory dry holes), 4.8 km of pipeline, and 23.5 km of seismic line. To account for flatter boreal terrain and older plays in the study area, pipeline and seismic line intensities were reduced by 25% resulting in 3.6 km of pipeline and 17.7 km of seismic line per production well. Based on Wilson et al. (2008), each new production well was associated with 0.2 ha of facilities.

For shale gas, footprint intensities were those applied by Nishi and Antoniuk (2010) in their exploration of natural gas development scenarios in the southern Dehcho. Each production well was associated with 0.67 exploration wells based on success rates from the Montney formation. Production wells were also accompanied by 15 km of seismic and 3 km of pipeline. Based on wells in the Montney Formation, four horizontal wells occurred on each 2 ha pad. For vertical and exploration wells, one well occurred per pad, where vertical wells covered 1 ha and exploration wells covered 0.5 ha. Based on Wilson et al. (2008), each new production well was associated with 0.2 ha of facilities.

The lifespan and size of footprints were based on assumptions from other scenario analyses completed in the region. Industrial plants were permanent[22]. Mine sites had a lifespan of 100 years[23]. Pipelines

---

[19] Table 11 from Wilson (2008) reports that average production is 175,000 barrels per ha. Assuming a mine productivity of 3200 m^3/ha/year over 20 years (i.e., cumulative production of 64000 m^3/ha), each mine ha is associated with 1.3 ha of other footprint (facilities, waste, tailings ponds).

[20] Based on table 13 from Wilson (2008). For consistency with other hydrocarbon types, each delineation well was assumed to cover 1 ha instead of Wilson's (2008) assumed 0.49 ha. This modification is supported by validation data from ongoing SAGD projects which indicate that nonproduction well pad area is approximately twice as prevalent as assumed by Wilson (2008).

[21] Footprint comparisons per m^3 of annual production for an assumed base case SAGD project (Wilson 2008) and validation data from 8 ongoing projects (Hague and Wilson 2009) are as follows.

a) Seismic: 6.35e-04 km/m^3 (base case) vs 6.05e-04 km/m^3 (validation);
b) Nonproduction wells: 2.22e-05 ha/m^3 (base case) vs 3.78e-05 ha/m^3 (validation);
c) Pipeline: 7.65-05 km/m^3 (base case) vs 6.6e-05 km/m^3 (validation);
d) Facility: 1.72e-05 ha/m^3 (base case) vs 3.09e-05 ha/m^3 (validation).

The validation data were not used to parameterize footprint intensity assumptions because the data are from ongoing SAGD projects and therefore may not be representative of the overall project footprint.

[22] Carlson (2011) assumed that industrial plants in the Al-Pac FMA area in northeastern Alberta are permanent. Similarly, Wilson (2008) assumed that industrial plants in northeastern Alberta are seeded to grass after 60 years which, in the context of a 50-year simulation, is essentially permanent.

[23] A mining footprint lifespan of 100 years reflects the business as usual assumption adopted by the Athabasca Landscape Team (2009).

had a lifespan of 70 years[24], but 25% of the 15 m right of way was reclaimed post-construction (Athabasca Landscape Team 2009). Based on a retrospective analysis of seismic line reclamation in northeastern Alberta (Lee and Boutin 2008)[25], existing 5 m wide seismic lines had a lifespan of 60 years. New seismic lines were low impact (2.5 m wide) with a lifespan of 20 years[26]. Production wells and access roads reclaimed 35 years post-closure[27]. Each exploration well covered 0.5 ha and reclaimed after 35 years[28]. Assumptions for road footprint are described in the transportation section of the methodology.

3.2 Forestry

The simulated timber harvest rate was based on annual allowable cut (AAC) and annual harvest data. A spatial dataset of Canada's commercial forest tenures (Lee et al. 2003) was used to identify tenures occurring within the study area and their respective AAC's. The study area's AAC was calculated as the sum of AAC's across tenures, adjusted based on the proportion of each tenure occurring within the study area (Table 6). Timber harvest in simulations was restricted to tenures, which accounts for 68%, 75%, and 75% of unprotected coniferous, deciduous, and mixedwood forest in the study area. Tenures and AAC's do not exist for the NWT portion of the study area. Instead, the moderate timber harvest

---

[24] ALCES Group (2011) assumed an average pipeline lifespan of 74 years in the Al-Pac FMA area, based on the rationale that approximately 35% of pipelines large flow (i.e., pipelines regulated by NEB) with a lifespan of 100 years and 65% of pipelines are small flow with a lifespan of 60 years. Nishi and Antoniuk (2010) assumed a pipeline lifespan of 100 years in the southern Dehcho. Wilson (2008) assumed that pipelines would be seeded to grass after 60 years, implying that it takes longer than 60 years for a pipeline footprint to return to its pre-disturbance condition land cover type.

[25] Lee and Boutin (2008) retrospective analysis of seismic line reclamation in northeastern Alberta over the past 35 years found that seismic was lost from the landscape at a median rate of 0.8% per year. This implies that approximately 50% of seismic is lost after 60 years. This may underestimate the lifespan of existing seismic lines because Lee and Boutin (2008) found that much of the seismic was "lost" to tracked access rather than natural vegetation.

[26] New seismic was assumed to have an average lifespan of 20 years. Wilson (2008) assumed a lifespan of 10 years for low impact seismic in northeastern Alberta, but this may underestimate seismic lifespan if 4D seismic programs become prevalent (Athabasca Landscape Team 2009). 4D seismic involves active use of seismic lines for multiple years, implying that the initiation of reclamation is delayed and that reclamation is slower due to vegetation disturbance and soil compaction associated with multiple visits (i.e., across years). Therefore, the lifespan of 4D seismic is likely multiple decades in length. About 25% of seismic activity in the region is 4D (Godfrey 2010). This is likely to increase over time given its utility for exploring insitu bitumen and shale gas reservoirs (Gray 2011, Uffen 2011).

[27] The lifespan assumption is based on Athabasca Landscape Team (2009) assumption that delineation wells and access require 35 years to reclaim. Wilson (2008) assumed that production wells reclaim to grass after 15 years in northeastern Alberta, implying that reclamation to natural landcover requires longer than 15 years. Nishi and Antoniuk (2010) assume reclamation occurs 5 years post-closure in the southern Dehcho. In contrast, MacFarlane's (1999) analysis of abandoned wellsites in the Al-Pac FMA area found that the stocking rate (i.e., based on the presence of established seedling) was 0% even for wellsites that had been abandoned for more than 20 years. ALCES Group (2011) assumed that reclamation of abandoned well sites requires several decades post-closure in the Al-Pac FMA area.

[28] The lifespan assumption is based on Athabasca Landscape Team (2009) assumption that delineation wells and access require 35 years to reclaim. Wilson (2008) assumed a lifespan of 10 years for exploration wells in northeastern Alberta whereas ALCES Group (2011) assumed a lifespan of 40 years due to poor stocking rates of abandoned well sites in the region (MacFarlane 1999).

level equaled the average harvest level in the Northwest Territories[29] over the past 10 years (28,717 m^3 coniferous and negligible deciduous; Canadian Council of Forest Ministers 2011). Timber harvest was restricted to Liard River, Cameron Hills, and Buffalo River Spatial Inventory Areas.

Timber harvest in the low and high scenarios was ±20% of the moderate scenario for consistency with assumptions for hydrocarbon production. The change in harvest level was distributed proportionally across the tenures, with the exception of the Northwest Territories where timber harvest declined to 0 in the low scenario and increased to the recommended sustainable annual harvest for the Dehcho Territory (109,000 m^3; PACTeam Canada 2003) [30] in the high scenario.

Table 6. The study area's annual allowable cut (AAC) by jurisdiction.

Jurisdiction	Coniferous AAC (m^3)	Deciduous AAC (m^3)
Alberta	12,321,283	9,295,068
British Columbia	2,900,422	129,817
Saskatchewan	1,509,066	1,313,310
Total	16,730,771	10,738,195

[29] The majority of NWT's timber harvest is likely to occur within the study area.
[30] Recommended sustainable annual harvest is specified for three regions: Cameron Hills (8,000 – 10,000 m^3), Lower Liard (88,000 m^3), and Buffalo River (11,000 m^3).

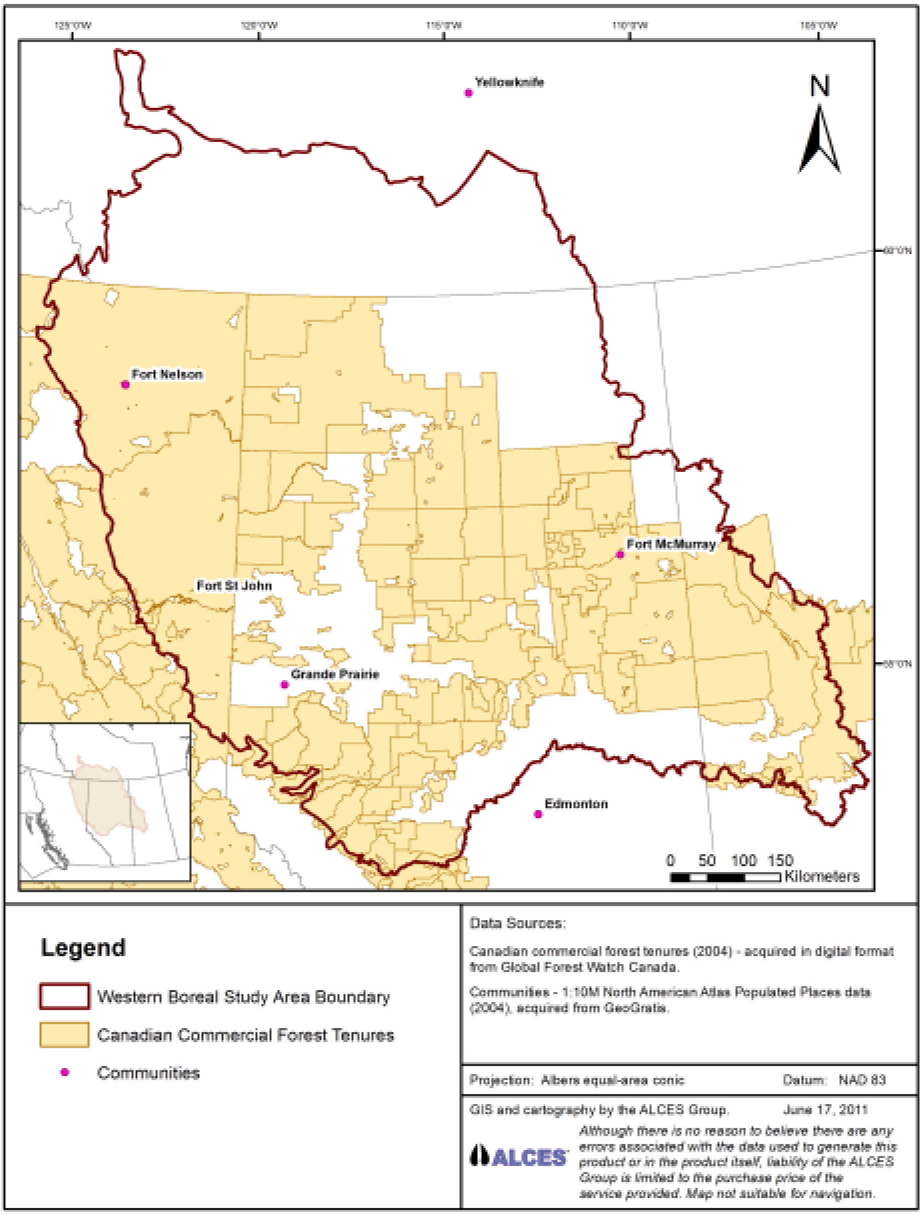


Figure 13. Commercial forest tenures within the study area.

Simulated timber harvest strategies reflected detailed forest management plans for two of the largest FMA's in the study area, the Alberta-Pacific (Al-Pac) FMA (Alberta-Pacific Forest Industries Inc. 2008) and the Upper Hay Forest Area (Tolko High Level Lumber Division and Footner Forest Products Ltd 2003). FMA area's from Alberta were selected to inform forestry assumptions given that 79% of the study area's AAC is located in Alberta. The Al-Pac FMA is located in the eastern portion of Alberta, in the Boreal Plains ecozone, whereas the Upper Hay Forest Area is located in the western portion of Alberta, in the Boreal Taiga ecozone.

Table 7. Assumptions describing the timber harvest strategy within the study area.

Forestry Parameter	Assumption
Minimum harvest age	60 years for hardwood stands and 80 years for softwood stands[31]
Minimum volume	50 m^3/ha[32]
Harvest sequencing	50% sequenced based on oldest first, 50% distributed across merchantable age-classes[33]
Merchantable structure retention	3% of green trees within cutblocks were not harvested[34]
Merchantable forest deleted from operable area (in addition to protected areas)	7% of merchantable forest in riparian buffers[35] 2% of merchantable forest as other deletions[36]
Cutblock lifespan	Cutblocks immediately began regenerating (i.e., transition to a stand with age=0 years), and regeneration failure is 0.
Fire salvage	25% of merchantable deciduous stands and 50% of merchantable coniferous stands that burn were salvaged. 50% of merchantable volume prior to fire was salvaged[37]
Industrial salvage	100% of industrial footprint was salvaged
Inblock roads	Inblock roads accounted for 3% of cut block area and reclaimed over 10 years, based on assumptions used in CEMA.

3.3 Agriculture

The study area overlaps with the portions of Saskatchewan, Alberta, and British Columbia that are most likely to see agricultural expansion in the future due to the availability of arable land (ArborVitae 2004). ArborVitae (2004) provided low and high estimates of future (year 2015) regional deforestation due to expansion of improved land (cropland, summer fallow, and tame or seeded pasture). The low estimate,

[31] The timber supply analysis presented in the Al-Pac FMP assumes minimum harvest ages of 60 years for hardwood stands and 80 years for softwood stands. The Upper Hay Forest area's forest management plan assumes minimum harvest ages of 70 years for hardwood and and 90 years for softwood. In ALCES, minimum harvest age is specified by 20-year seral stages (i.e., 0-20, 21-40, 41-60, 61-80, etc.). As such, it is not possible to set minimum harvest ages of 70 and 90 years; instead, the minimum harvest ages from the Al-Pac FMA were used.

[32] Al-Pac's timber supply analysis assumes a minimum volume requirement of 50 m^3/ha.

[33] Although forestry companies tend to sequence oldest stands first for harvest, various spatial constraints (delivered wood cost, two-pass harvest system, etc.) are such that a full oldest first harvest sequence is not realized. A more realistic assumption is that 50% of the harvest is sequenced oldest first with the remainder of the harvest distributed randomly across merchantable age-classes (Dave Cheyne, pers comm).

[34] Forest management plans often call for retention of a portion of merchantable forest in order to maintain forest structure for wildlife and promote natural stand dynamics. Al-Pac retains 5% of merchantable volume, whereas retention of 1% of merchantable volume is the target in the Upper Hay Forest Area.

[35] Operating ground rules in Alberta specify a 100 m no-harvest buffer around lakes, 60 m buffer around large permanent watercourses, and 30 m buffer around small permanent watercourses. These buffers account for 6.7% of the merchantable landbase in the Upper Hay Forest Area and 7.3% of the merchantable landbase in the Upper Hay Forest Area. Merchantable landbase refers to the operable area plus riparian buffers and other operable deletions (see the footnote below for details).

[36] Other areas deleted from operable area include land-use dispositions (e.g., protected notations), aboriginal reserves, private land, the valleys of large rivers (e.g., Athabasca and Clearwater in the Al-Pac FMA and Ponton in the Upper Hay Forest Area), and other areas deemed unsuited for timber harvest (e.g., Peace River Islands in the Upper Hay Forest Area). Such areas account for 1.4% and 2.2% of the gross areas of the Upper Hay Forest Area and Al-Pac FMA.

[37] ALCES Group 2011

which assumes poor commodity prices and a minimum of available arable land, was applied in the low scenario. The high estimate, which assumes good commodity prices and a higher level of available arable forested land, was applied in the high scenario. The mid-point between the two rates of agricultural expansion was applied in the moderate scenario. Estimates of future growth are less than historical growth rates due to limited availability of undeveloped arable land[38]. Growth rates were proportional to the degree of overlap of the agricultural regions with the study area (Table 8). ArborVitae (2004) did not estimate agricultural growth in Canada's territories due to the absence of significant agriculture today. However, scenarios assessed during the development of the Dehcho Territory (located in southern NWT) land use plan assumed that 0.5 percent of areas with medium or high agriculture potential would be developed each year (DCLUPC 2006), which accounts for 9 km^2/year in the southern portion of the territory (Carlson et al. 2007). This assumption was applied to model agricultural expansion in the Northwest Territories in the high scenario. Agriculture did not expand in the Northwest Territories during the low scenario, and the moderate scenario's expansion rate was half that of the high scenario. Across all scenarios, the ratio between crops and pasture remained constant.

Table 8. Assumptions for future deforestation due to agriculture, based on ArborVitae (2004).

Region	1981-2001 growth rate (km^2/year)	Overlap with study area	Low future growth rate (km^2/year)		High growth rate (km^2/year)	
			Full region	Study area	Full region	Study area
BC Peace Region	21	52%	5	2.6	30	15.6
Alberta ARs 5, 6, & 7	364	76%	25	18.9	300	226.9
Saskatchewan ARs 8 & 9	80	18%	5	0.8	10	1.8

3.4 Settlements

According to the 2006 census, the study area contains a population of 443,960[39]. Exponential population growth rates were estimated for each census division occurring within the study area using census data from 1991 to 2006[40]. To inform spatial modeling of human population growth, current population and population growth rate estimates were summarized by tertiary watershed based on their overlap with census divisions and subdivisions. Future population within each tertiary watershed was modeled by applying the watershed's growth rate to its current population. Averaged across the study area, the population growth rate was 1.16%, resulting in a population of 790,287 by the end of the 50-year simulation. The area of settlements[41] grew proportionally to the human population. The

---

[38] The location of arable land is based on the Canada Land Inventory's agriculture layer (http://geogratis.cgdi.gc.ca/cgi-bin/geogratis/cli/agriculture.pl). Classes 1-5 can support economically viable agricultural production, classes 1-3 can support crop production (Canada Land Inventory 1976)

[39] The population estimate is based on the 2006 populations of census subdivisions that area located within the study area. The population contributed by census subdivisions that overlapped the study area boundary was based on the proportion of the census subdivision located within the study area.

[40] Population growth rate was estimated using census division population estimates available from Statistics Canada, which included the years 1991, 1996, 2001, and 2006. Population growth was assessed using census divisions rather than the more detailed census subdivisions because census subdivision boundaries changed in 1996.

[41] Two-thirds of the existing rural residential area overlaps with farmland and is assumed to be agricultural residences.

population growth rate for the low (0.77%) and high (1.56%) scenarios were modified from the moderate scenario based on the relative change in employment[42].

The population growth rate estimated from census division data is substantially less than growth rates estimated for the two most populous municipalities in the region (Grande Prairie and Fort McMurray/Wood Buffalo) for which longer term data are available from Alberta Municipal Affairs and Housing (2010; Figure 14). The high growth rates for these settlements suggest that the 1.16% growth rate assumed for the scenario analysis is conservative. The high population growth rates of the settlements also suggest that population growth is higher in urban centres relative to the remainder of the study area. As of 2006, 82% of Alberta's population was urban as opposed to rural (Statistics Canada 2006b). Simulations assumed that 82% of future population growth will continue to occur at existing settlements.

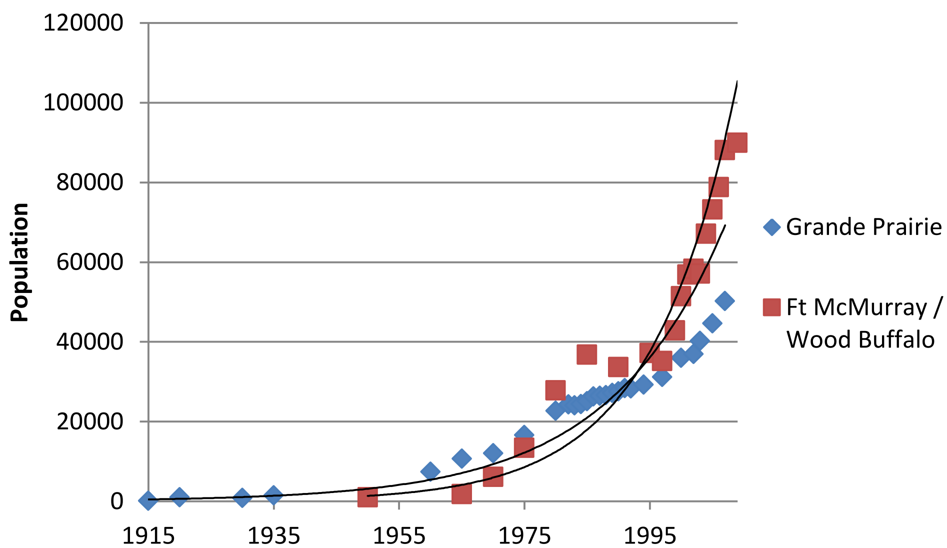


Figure 14. Exponential models fit to historical population data from Grande Prairie and Ft. McMurray/Wood Buffalo exhibit growth rates of 5.4% and 7.4%, respectively.

3.5 Transportation

Simulated expansion of the road network was based on existing relationships between the road network and land uses, including settlements, forestry, energy exploration, and agriculture. To assess these relationships, road length was related to land-use activities across 231 census subdivisions that have at least 50% of their area within the study area. The dataset for the analysis included the following measures for each census subdivision:

1. road length in km, based on the Geobase national road network dataset,

[42] The simulated population growth rate for the low and high scenarios was based on a comparison of the increase in employment during the simulation for each scenario. The increase in population was during the low scenario was 66% that of the moderate scenario, whereas the increase during the high scenario was 134% that of the moderate scenario. The population growth rates for the low and high scenarios were therefore 66% and 134% that of the moderate scenario.

2. human population, based on the 2006 Census (Statistics Canada 2006b),
3. improved agricultural land (crops, fallow, and tame or seeded pasture), based on the 2006 Census for Agriculture (Statistics Canada 2006a),
4. non-abandoned well sites (Peter Lee, pers. comm.), and
5. cumulative timber harvest based on overlap of CSD's with forestry tenures (Lee et al. 2003). A CSD's annual allowable cut (AAC) was first estimated based on the AAC's of tenures that it overlapped. Next, a CSD's annual harvest was estimated by reducing its AAC to account for the tendency of provincial timber production to under-represent the AAC[43]. Finally, the annual harvest was converted to a cumulative harvest based on the assumption that tenures in the study area are, on average, a third of the way through harvesting the first 80-year rotation[44].

Multiple linear regression was then applied to the data set to relate road length to human population, agricultural land, well sites, and timber harvest. The coefficient for human population was not significant ($p=0.896$), and was therefore removed from the model. A multiple linear regression model incorporating well sites, timber harvest, and agricultural land successfully captured the majority of the variation in road length, achieving a coefficient of variation of 0.91 with significant coefficients for each land-use parameter ($p<0.000001$). Based on the analysis, it was concluded that subregional land use patterns are a reasonable predictor of road density. Coefficients from the multiple regression model are presented in Table 9. The regression model's intercept term of 28.3 implies that the coefficients do not account for 7.6% of the average road length in a census subdivision. For example, 7.6% of road development is assumed to be independent of the simulated land use sectors and is not included in future projections. The coefficients were applied in simulations to derive local road expansion as follows:

1. 5.60-01 km of private road will be created for each ha of new well sites
2. 1.94e-05 km of private road will be created for each m^3 of timber harvest
3. 9.53e-03 km of public road will be created for each ha of new farmland

These estimated rates of local road development, while approximate, are similar to other analyses for the region. Schneider and Dyer (2006) report that a SAGD project in northeastern Alberta require 0.457 km of roads per ha of production well[45]. A geospatial analysis of footprint associated with young to mature foothills conventional oil and gas plays in Alberta found an average road density of 4.0 km/well, which likely exaggerates the road requirements of conventional oil and gas development in the study area due to the flatter boreal terrain and older plays. The minor road network (excluding well site access roads) in the Al-Pac FMA area is expected to grow at a rate of 50 km/year which, when applied to the AAC of 2.27 million m^3, is equivalent to 2.20e-05 km/m^3 (ALCES Group 2011).

---

[43] Over the past 10 years, the proportion of provincial AAC that has been harvested, on average, has ranged from 46% (coniferous harvest in Saskatchewan) to 97% (coniferous harvest in Alberta). See the Forestry subsection in the methods for details.
[44] Many of the tenures in the region were not allocated until the 1980's and 1990's (Schneider 2002).
[45] Infrastructure for the SAGD development included 48 well pads, each with an average size of 4.1 ha, and 89.9 km of road. Therefore, 89.9 km of road were required for 196.8 ha of production wells, for an average of 0.457 km/well ha.

Application of the regression coefficients to derive simulated road length approximates the assumption that the existing ratio between road length and land use will remain constant. The assumption was applied spatially in Mapper by locating roads in grid cells relative to each cell's land use rates. Roads were permanent, with the exception of well site access roads which had a lifespan equivalent to that of the well site. Existing roads within the study area were permanent with the exception of those classified as "resource/recreation" by Geobase National Road Network dataset, which were assumed to be existing well site access roads.

Table 9. Coefficients and p-values of explanatory variables from a multiple linear regression, where road length by census subdivision was the response variable.

Land-use parameter	**Non-abandoned well site area (ha)**	**Cumulative timber harvest (m^3)**	**Agricultural land (ha)**
Coefficient	5.60e-01	1.94e-05	9.53e-03
P value	1.56e-13	4.0e-07	1.00e-39

Culverts were applied to roads at a rate of 0.2 per km, based on an estimate of the existing density of culverts in the study area[46]. Culverts can impede fish movement in fish-bearing streams if water velocity is too high, if the culvert becomes blocked, or if the downstream end of a culvert becomes suspended (hangs) above water level as a result of scouring by outflow. Impediment of fish movement fragments fish habitat and potentially decreases access to spawning and rearing areas. At the start of simulations, 40% of culverts were hanging based on Park et al. (2008).

To track the development of problem culverts through time, ALCES® applies a relationship between annual rainfall and culvert failure rate based on data from the foothills region in Alberta (Michael Sullivan, pers. comm.). To assess its suitability to the study area, the relationship was compared to the culvert failure odds ratio of 1.065 estimated by Park et al. (2008) for boreal Alberta. For instance, hung culverts are 1.065 times more abundant in year x+1 than in year x. Assuming that 30% of culverts are hung at the start of a simulation, the odds ratio predicts that the proportion of hung culverts the next year will be 1.065*0.3 = 0.320. This is equivalent to an annual failure rate of 2.9% (i.e., 2.9% of non-hanging culverts develop hang during the year). In contrast, the culvert failure rate assumed by ALCES® under average rainfall is 1.7%. In summary, it appears that the culvert failure rate assumed by ALCES® may moderately underestimate the actual failure rate expected in boreal Alberta. It was also assumed that monitoring and maintenance results in the replacement of 2% of problem culverts each year (ALCES Group 2011).

[46] An intersection of the road and stream networks in the study area resulted in 19,595 intersections with roads. The stream network was based on the National Hydro Network dataset (Centre of Topographic Information 2004); this excluded rivers from the analysis, which are assumed to be crossed by bridges. Assuming that 92.5% of crossings are culverts (ALCES Group 2011) results in 18,125 culverts on 90,607 km of road, for a density of 0.2 culverts per km of road.

4 Wildlife, Environment, and Economy Indicators:

4.1 Landscape Composition

Four indicators were assessed to summarize the effect of land use and natural disturbances on the composition of the landscape: old forest area, proportion of landscape younger than 30 years, area of anthropogenic footprint, and anthropogenic edge. Old forest was assessed because of the high species richness that these ecosystems support (e.g., Schieck and Song 2006) due to their higher structural complexity and spatial heterogeneity (Stelfox 1995). Old forest were those seral stages considered to be over-mature (i.e., stands that have surpassed the mature stage and have declining growth volume rates and increased mortality). In the boreal region, stands are considered over-mature at year 100 for deciduous and mixedwood forest and at year 120 for coniferous forests (Alberta-Pacific Forest Industries 2008). Proportion of landscape younger than 30 years was assessed due to the negative impact of this attribute to woodland caribou (see woodland caribou indicator description for details). Anthropogenic footprint by sector was tracked to assess the degree to which each sector converts natural landcover to land-use footprint. Anthropogenic edge was also tracked due to the numerous impacts of anthropogenic edge including direct mortality (e.g., increased angling and hunting facilitated by access), human access, habitat loss, and invasion by exotics (Trombulak & Frissell 1999). When calculating anthropogenic edge, linear footprints were assumed to have one edge, whereas polygonal footprints had four edges.

4.2 Moose

The response of moose habitat to changes in landscape composition was assessed using a habitat suitability index (HSI) model developed for northeastern Alberta. HSI models are knowledge-based (as opposed to empirical) models that can incorporate information from a variety of sources. The moose HSI is based on literature review and expert opinion. The model was originally developed for the Cumulative Environmental Management Association (www.cemaonline.ca), and subsequently revised through the Lower Athabasca Regional Planning process.

The HSI model combines information related to habitat availability and quality to calculate an index that ranges from 0 to 1. Steps required to calculate the index are summarized below. More details are available in Appendix 6.3.1.

a) For each cover type (including footprints), habitat availability is assessed as the product of its proportional abundance and its habitat value. Habitat values is a parameter that expresses the utility of a cover type to the species, where 0 indicates no utility and 1 indicates capacity to support the species' maximum density. To account for avoidance and mortality, the habitat value of landcover in proximity of anthropogenic footprints such as roads can be reduced by applying buffers to footprint and down-weighting the value of habitat within the buffer by a proportional use coefficient, i.e., the proportion of habitat within the buffer that is used. The width of the buffers can be reduced to account for strategies that limit human access and therefore the impact of anthropogenic footprints.

b) Habitat quality is a value ranging from 0 to 1 that incorporates the effect of other landscape attributes on habitat such as forest age and human population density. For each relevant landscape attribute, a response surface ranging from 0 to 1 dictates the relationship between habitat quality and the status of the attribute. Each attribute is given a weight, whereby the sum of weights equals 1. Habitat quality for each landcover type is then calculated as the sum of the products of the quality of each habitat attribute and its weight.

c) Habitat suitability (i.e., HSI) is then calculated as the sum of the products of each cover type's habitat availability and habitat quality.

The moose HSI assumes that deciduous forest has the highest habitat value, followed by mixedwood forest and shrubland due to the capacity of these cover types to provide browse and cover. To account for the impact of human access, especially hunting, anthropogenic footprints are buffered by 50 to 200 m when calculating habitat availability. The exception is protected areas, where buffers are removed to incorporate the effect of an extensive reduction in human access[47] (Sullivan 2011). Forest age is assumed to be the only determinant of habitat quality. Although linear disturbance density and human density were also included as habitat quality attributes in the original model developed for CEMA, they were removed here to avoid double counting (i.e., exaggerating) the impact of human access which is already represented by footprint buffers. Habitat value and quality parameters for the moose HSI are provided in Appendix 6.3.1.

Status of the moose HSI was assessed relative to an estimated range of natural variation. Departure from RNV was used to infer risk to species (e.g., moose) by applying a set of risk categories that are proposed Alberta's Biodiversity Management System and based on those used by International Union for the Conservation of Nature (Michael Sullivan, ASRD, pers comm). The categories are intended for measures that have a positive and linear relationship with wildlife abundance, which is a typical assumption of HSI models. The four categories are; 1) low risk, defined as a decline of no more than 30% from the undisturbed state (RNV), 2) moderate risk, defined as a decline of 30% to 50% from RNV, 3) high risk, defined as a decline of 50% to 80% from RNV, and 4) very high risk, defined as a decline of more than 80% from RNV. When assessing departure from RNV, the lower bound of the RNV was used.

4.3 Fisher

As with moose, the response of fisher habitat to simulated landscape changes was assessed using a HSI model (see the previous section on the moose HSI for a general description of HSI models). The fisher HSI was based on literature review and expert opinion. The model was developed for the Cumulative Environmental Management Association.

The fisher HSI assumed that upland coniferous and mixedwood forest have the highest habitat value due to the capacity of these cover types to provide cover and prey throughout the year. To account for the impact of human access, especially trapping, habitat value was decreased by 90% within 100 m of anthropogenic footprints. As with moose, the exception was protected areas where buffers were removed to incorporate the effect of limited human access. Habitat quality was determined by forest

---

[47] Based on interviews with wildlife biologists familiar with northern Alberta, full access management is assumed to cause a doubling in moose density (Sullivan 2011). Examples provided by Sullivan (2011) of extensive access management include protected areas such as Kananaskis Country, Willmore Wilderness Reserve, and National Parks. Sensitivity analyses in ALCES established that a doubling in moose density is consistent with buffer widths of 0 m around human footprints.

age[48], with older forest having higher quality due to the importance of canopy closure for cover, and large-diameter overstorey trees for dens. Habitat value and quality parameters for the fisher HSI are provided in Appendix 6.3.2.

As with the moose HSI, the status of the fisher HSI was interpreted using risk categories that are based on departure from the estimate RNV.

4.4 Caribou

The response of caribou to simulated landscape change was assessed using a model that relates relative rate of population change to landscape composition. The model was estimated by Boutin and Arienti (2008) from Alberta caribou data. Caribou finite rate of population increase was calculated for each of 10 herds from population data collected over the period 1993-2006. Disturbance variables (industrial footprint, burns, cutblocks) were also calculated for each herd's range. Regression was then applied to identify the best model that related finite rate of increase (dependent variable) to range disturbance (independent variable). The resulting model was:

Finite rate of increase = 1.0184 – (0.0234 * linear_feature_density) – (0.0021 * %_young_habitat)

where:

- linear_feature_density = combined density (km/km^2) of roads, pipelines, and seismic lines, and
- %_young_habitat = percent of the landscape disturbed by fire or timber harvest within the past 30 years.

The typical interpretation of a finite rate of increase is that values below 1 imply population decline. However, simulations that exclude historical and future land use produce finite rates of increase below 1 most of the time. Values below 1 therefore do not necessarily imply population decline for this study. To emphasize that a value below 1 should not necessarily be interpreted as population decline, the response variable is referred to in this study as the caribou population index. Instead of comparing the caribou population index to the value of 1, the index is interpreted using a set of thresholds developed for assessing risk to caribou ranges in northeastern Alberta (Athabasca Landscape Team 2009). The thresholds incorporate three levels of risk to population persistence; 1) low, defined as index values that are greater than 0.99, 2) moderate, defined as index values that are between 0.95 and 0.99, and 3) high, defined as index values that are below 0.95.

In ALCES, a single value of the caribou population index is calculated based on the linear feature density and landscape disturbance across the entire study area. In ALCES Mapper, a separate value of the caribou population index will be calculated for each herd range within the study area based on linear feature density and landscape disturbance within each range. Within protected areas, the caribou population index was increased by 0.015 to incorporate the small potential benefit of access management due to reduced poaching and road-kill (Sullivan 2011).

---

[48] The fisher HSI model from CEMA also included forest structure and snag density as habitat quality elements. However, because information does not exist to reliably simulate these attributes, forest age is being used to assess habitat quality.

4.5 Index of Native Fish Integrity

The status of the fish community was assessed using the index of native fish integrity (INFI), a measure that conveys changes in abundance and composition of fish species with a value ranging from 1 (undisturbed community) to 0 (highly disturbed community). Fish communities associated with different INFI values are presented in Table 10. The INFI response to scenarios was estimated using relationships with human population density, density of access, watershed discontinuity, and stream flow developed during a workshop held with regional fishery experts. The workshop was held to inform scenario analyses completed by CEMA in northeastern Alberta. However, the relationships between INFI and the risk factors hold across the project's study area (Dr. Michael Sullivan, pers comm). Within protected areas, the effect of human population density and access density on INFI was reduced to incorporate the effect of extensive access management (Sullivan 2011).

INFI model values are presented in Appendix 6.3.3. As with the moose and fisher HSI's, the status of the INFI was interpreted using risk categories that are based on departure from the RNV value which, in the case of INFI, is equal to one.

Table 10. Fish community descriptions associated with INFI values of 1, 0.5, and 0 (from Sullivan 2006).

Fish Habitat Type	INFI = 1	INFI = 0.5	INFI = 0
Rivers	Abundant walleye and pike (all sizes). Common catches of Arctic grayling, slimy sculpin, burbot, trout-perch, dace and suckers.	Abundant small walleye and pike, few large fish. Common catches of burbot, trout-perch, dace, and suckers. Few Arctic grayling and sculpin.	Very few small walleye and pike, few large fish. Rare catches of Arctic grayling and burbot, trout-perch and dace. Abundant suckers and fathead minnow.
Large Streams	Abundant Arctic grayling and small pike (depending on slope of stream). Common catches of larger walleye, pike, slimy sculpin, dace, suckers and lake chub. Rare catches of fat head minnow and brook stickleback.	Abundant small Arctic grayling and small pike (depending on slope of stream). Rare catches of larger walleye, pike, and Arctic grayling. Common catches of suckers, lake chub, fathead minnow and brook stickleback.	Few small Arctic grayling and small pike (depending on slope of stream). Very rare catches of larger walleye, pike, and Arctic grayling. Abundant catches of suckers, lake chub, fathead minnow and brook stickleback.
Small Streams	Abundant small Arctic grayling and small pike (depending on slope of stream). Common catches of dace, suckers, stickleback and fathead minnow.	Rare small Arctic grayling and small pike (depending on slope of stream). Common catches of suckers, stickleback and fathead minnow.	Very rare small Arctic grayling and small pike (depending on slope of stream). Abundant catches of suckers, stickleback and fathead minnow.
Large Lakes (> 300 ha)	Abundant walleye and pike (all sizes). Common catches of burbot and trout-perch.	Abundant walleye and pike. Few large fish. Rare catches of burbot, trout-perch, common catches of suckers, lake chub.	Very few small walleye and pike. Few large fish. Rare catches of burbot, trout-perch. Abundant catches of suckers, lake chub.
Small Lakes (< 300 ha)	No larger fish. Abundant brook stickleback and fathead minnows. Common catches of suckers and some small pike.	No larger fish. Abundant brook stickleback and fathead minnow. Common catches of suckers and some small pike.	No larger fish. Abundant brook stickleback and fathead minnow. Common catches of suckers and some small pike.

4.6 Songbirds

To assess the response of songbirds to the simulated landscape changes, an old forest bird index was developed using bird density models[49] developed by the Boreal Avian Modelling Project (www.borealbirds.ca) from hundreds of point counts collected across Alberta's boreal region. The models relate male songbird density to forest type (deciduous, pine, upland spruce, lowland spruce[50], and mixedwood) and age (20-year seral stages), after correcting for differences in sampling effectiveness across point counts. Density estimates were available for each of four forested regions in Alberta: Lower Peace, Lower Athabasca, Upper Athabasca, North Saskatchewan, and Red Deer. Three of these regions overlap with the study area: Lower Peace, Lower Athabasca, and Upper Athabasca. The density estimates used to derive the old forest bird index were area-weighted averages of the density estimates from these three regions. When calculating the area-weighted average, the BC and NT portions of the study area were assumed to be similar to the Lower Peace region, whereas Saskatchewan was assumed to be similar to the Lower Athabasca.

The old forest bird index incorporated density estimates for the species identified by ABMI (2012) as Boreal Plains old-forest specialists: red-breasted nuthatch, winter wren, pine siskin, western tanager, white-winged crossbill, swainson's thrush, cape may warbler, bay-breasted warbler, black-throated green warbler, solitary vireo, boreal chickadee, golden-crowned kinglet, and brown creeper. For each species, the density estimates were averaged across forest types and then standardized such that the maximum density value equaled 1. The standardized density values were then averaged across species to create an old forest bird index value for each seral stage, thus higher index values indicate seral stages that support higher densities of various old forest bird species (Figure 15). The index was applied as an intactness value, which entailed expressing a simulated future landscape's bird index as a proportion of the estimated natural landscape's bird index value. This required first calculating the older forest bird index value associated with each tertiary watershed's estimated natural landscape composition[51]. Old forest bird intactness for a watershed's simulated future landscape composition was then calculated by dividing its old forest bird index by the natural index value. Intactness values were categorized into levels of risk based on a scoring system applied by Partner's in Flight to identify bird conservation objectives from population trends (Rosenberg and Blancher 2005). Species that have declined by at least 50 percent over a 30-year period are assessed by Partner's in Flight as requiring a recovery objective of twice the current population. Species that have declined by 15-50 percent are given a recovery objective of 1.4 times the current population. Based on this scoring system, intactness values below 0.5 (i.e., >50% decline relative to natural) were interpreted as high risk to the old forest

---

[49] The Boreal Avian Modelling Project developed the models using a generalized linear modelling framework. The negative binomial error family and log link achieved the best model fit, as expected given the abundance of low counts in the point count data.

[50] Density estimates for pine, upland spruce, and lowland spruce where averaged because the simulation modelling only tracked a single coniferous forest type. The average was weighted by the relative abundance of the three coniferous forest types in the Regional Municipality of Wood Buffalo, a 55 thousands km^2 landscape in the study area. The relative abundance of the forest types was 51% pine, 21% lowland spruce, and 28% upland spruce (Andison 2005).

[51] Each watershed's natural landscape composition was estimated by removing anthropogenic footprints. The natural forest age-class composition was calculated in ALCES by applying a deterministic fire rate of 1.1% per year.

bird community and intactness values between 0.5 and 0.85 (i.e., 15-50% decline relative to natural) were interpreted as moderate risk to the old forest bird community. Intactness values greater than 0.85 were interpreted as low risk.

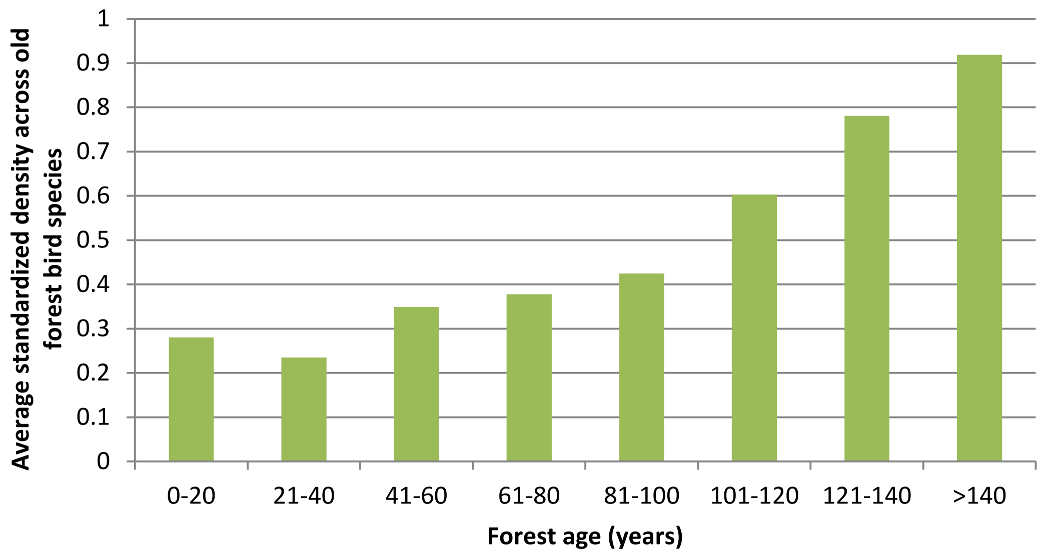


Figure 15. Old forest bird index values associated with each seral stage.

4.7 Water quality

Water quality was assessed by tracking changes to nitrogen and phosphorus runoff, parameters that are negatively related to overall water quality. Runoff associated with simulated landscapes was estimated by applying runoff (tonnes/ha/year) coefficients calculated for Alberta's Boreal Forest Natural Region (B. Donahue, pers. comm.). The coefficients were based on event mean concentrations and associated methods from the literature, yielding a linear relationship between precipitation and export. Runoff coefficients were calculated from each land cover type's precipitation x export relationship based on the average annual precipitation for Alberta's Boreal Forest Natural Region. The runoff coefficients are presented in Appendix 6.3.4. For each water quality parameter, an intactness value was then calculated for each watershed by dividing the runoff associated with the simulated future landscape composition by the runoff associated with the estimated natural landscape composition.

4.8 Water use

Water consumption was assessed by tracking water use, which refers to the amount of water that is consumed or lost (i.e., evaporation or seepage) and not available for immediate reuse. As described below, coefficients relating water use to bitumen production[52], timber production, agricultural land use, and human population (Table 11) were developed using water use data from Alberta's water basins[53] that overlap with the project study area (Alberta Environment 2007). The water use data are not useful, however, for estimating water use associated with shale gas production because shale gas production is

[52] Bitumen production will be the focus when assessing water use by the hydrocarbon sector because it dominates water use by the industry. In 2005, 97% of the water used by the petroleum sector in northern Alberta's basins was related to bitumen production.
[53] Water basins overlapping with the study area include the Athabasca, Peace/Slave, Beaver, Liard, and Hay.

currently limited in Alberta. Hydraulic fracturing for shale gas production requires between 7.5 and 30 million litres of water per well (Thomson and Shaw 2011). Given that each horizontal shale gas well is assumed to produce 155 million m^3, water consumption is approximately 1.21 e-004 m^3 of water per m^3 of gas. The use of surface water relative to groundwater during hydraulic fracturing was assumed to be the same as for insitu bitumen production (60% surface and 40% ground).

- Livestock production: in 2005, livestock were raised on 1,480,653 ha of tame/seeded pasture and used 8490 dam^3 of surface water and 5804 dam^3 of groundwater in northern Alberta basins.
- Crop production: in 2005, crops were produced on 6,398,480 ha of land[54] using 5,457 dam^3 of surface water in northern Alberta basins.
- Mineable bitumen production: in 2005, 31,998,000 m^3 of mineable bitumen were produced (CAPP 20011) using 158,077 dam^3 of surface water and 12,224 dam^3 of groundwater.
- Insitu bitumen production: in 2005, 57,550,227 m^3 of insitu bitumen were produced (CAPP 20011) using 15,402 dam^3 of surface water and 10,465 dam^3 of groundwater.
- Timber production: in 2005, the forestry sector in Alberta used 19,902 dam^3 of surface water and 517 dam^3 of groundwater to produce 27,545,885 m^3 of timber (Canadian Council of Forest Ministers 2011).
- Municipal/commercial/industrial: 383,383 people live in northern Alberta water basins. In 2005, municipal, commercial, and industrial activities not captured by the petroleum, forestry and agriculture coefficients used 22,155 dam^3 of surface water and 5,628 dam^3 of groundwater[55].

The bitumen water use coefficients were compared with those adopted by the Royal Society of Canada (2.5 and 0.5 m^3 water for each m^3 of mineable and insitu bitumen, respectively; Gosselin et al. 2010). The total (i.e., surface and groundwater) water use coefficient for insitu bitumen compared favourably (0.45 m^3 vs 0.5 m^3). However, the water use coefficient for mineable bitumen was substantially larger (5.32 m^3 vs 2.5 m^3). To avoid exaggerating water consumption attributable to mineable bitumen production, the water use coefficient used by the Royal Society of Canada was adopted (i.e., 2.5 m^3 per m^3 of mineable bitumen production[56]). The coefficient was divided between surface and groundwater use based on the relative quantities of water taken from the two sources for mineable bitumen production in 2005.

Table 11. Water use coefficients.

Sector	Surface Water	Ground Water
Municipal/commercial/industrial water use per person	66.46 m^3	16.88 m^3
Livestock water use per ha of tame/seeded pasture	14.17 m^3	9.69 m^3
Crop water use per ha of cropland (including summerfallow)	2.11 m^3	0
Water use per m^3 of mineable bitumen production	2.32 m^3	0.18 m^3
Water use per m^3 of insitu bitumen production	0.27 m^3	0.18 m^3
Water use per m^3 of shale gas production	7.26 e-005 m^3	4.92 e-005 m^3

[54] Includes 5,926,923 ha of cropland and 471,557 ha of summerfallow.
[55] Not included in municipal/commercial/industrial water use is water consumption related to water management and habitat enhancement.
[56] The resulting average water use coefficient for mineable and insitu bitumen production (1.475 m^3 per m^3 of bitumen production) is moderately less than CAPP's (2010) water use intensity estimate of 1.66 m^3/m^3.

Water use per m^3 of timber production	0.72 m^3	0.02 m^3

To aid in interpretation, surface water use was compared to the flow of the Mackenzie River. The Mackenzie watershed incorporates a large portion of the study area and its tributaries include other major rivers in the region such as the Athabasca, Peace, Slave, Hay, and Liard. Before exiting the study area (i.e., at its junction with the Liard at Fort Simpson) the average annual flow of the Mackenzie between 2000 and 2009 was 7206 m^3/second or 227 billion m^3/year[57].

4.9 Emissions

Simulations tracked GHG, sulphur oxide, and nitrogen oxide emissions associated with hydrocarbon, forestry, and agriculture production using emission coefficients calculated from various emission inventories and reports. Emissions are limited to those assumed to occur within the study area, including: primary forestry manufacturing, primary agriculture, and the upstream oil and gas industry.

4.9.1 Greenhouse gas emissions

In their review of GHG emissions associated with crude oils, The National Energy Technology Laboratory (Gerdes and Skone 2009) estimated that extraction and preprocessing emissions are 0.0352 tonnes of carbon dioxide equivalent (tCO_2e)/barrel (0.2218 tCO_2e/m^3) for conventional oil and 0.1115 tCO_2e/barrel (0.7025 tCO_2e/m^3) for bitumen from Canada's oilsands. This estimate of emissions from bitumen production included upgrading, however, of which only a portion occurs within the study area. Instead, GHG coefficients for bitumen production were based on McCulloch et al.'s (2006) who provide separate emission estimates for extraction and upgrading: 0.028 tCO_2e/barrel (0.176 tCO_2e/m^3) for bitumen mining and extraction; 0.052 tCO_2e/barrel (0.327 tCO_2e/m^3) for in-situ bitumen production; and 0.052 tCO_2e/barrel (0.327 tCO_2e/m^3) for bitumen upgrading[58]. Given that approximately 36% of bitumen upgrading occurs at onsite upgraders[59], bitumen upgrading emissions within the study area is approximately 0.0187 tCO_2e/barrel (0.118 tCO_2e/m^3). Greenhouse gas emissions associated with upstream natural gas production[60] were based on estimates from Natural Resources Canada's GHGenius model ($(S\&T)^2$ Consultants Inc. 2010): 0.0001029 tCO_2e/m^3 for conventional natural gas and 0.00016655 tCO_2e/m^3 for shale gas.

The forestry GHG coefficient was based on NCASI's carbon profile of the Canadian Forest Products Industry (Upton et al. 2007). In 2005, Canada's total industrial roundwood harvest of 164,489,000 m^3 (Canadian Council of Forest Ministers 2011) was associated with forestry manufacturing emissions (not including secondary manufacturing, transport, landfill, or forest carbon) of 24.6 million tCO_2e (Upton et al. 2007), for an intensity of 0.1496 tCO_2e/m^3.

---

[57] Mackenzie flow rate at Fort Simpson extracted from Environment Canada's HYDAT database.

[58] McCulloch et al. (2006) provide emission intensities for one low and one high emissions intensity operation. To be avoid exaggerating emissions, the low emissions intensity operation was use to parameterize the emissions coefficient. The resulting estimates are moderately higher than CAPP's (2010) estimate of 0.49 tCO_2e/m^3. Combined extraction and upgrading emission intensity estimates from McCulloch et al. (2006) are 0.503 tCO_2e/m^3 surface bitumen and 0.654 tCO_2e/m^3 insitu bitumen, for an average of 0.579 tCO_2e/m^3.

[59] Griffiths and Dyer (2008) report that of the approximately 60% of bitumen that is upgraded in Alberta, 60% is likely to be upgraded at onsite upgraders.

[60] Upstream natural gas emissions do not include feedstock transmission, fuel production, fuel distribution and storage, fuel dispensing, or fugitive and venting emissions except for those associated with gas processing.

The GHG emissions coefficient for the agriculture sector was based on emissions by Alberta's agriculture sector in 2006, according to the National Greenhouse Gas Inventory (Environment Canada 2010). GHG emissions in 2006 included 8775 thousand tCO_2e from enteric fermentation, 2284.4 thousand tCO_2e from manure management, and 8008.6 thousand tCO_2e from agriculture soils. That same year, improved agricultural land (crops, fallow, and tame pasture) covered 13,011,655 ha in the province, resulting in emission intensities of 0.6744 tCO_2e/ha, 0.1756 tCO_2e/ha, and 0.6155 tCO_2e/ha for enteric fermentation, manure management, and agriculture soils, respectively. However, average provincial enteric fermentation and manure management emission intensities likely exaggerate emissions in the study area because livestock densities are lower in the boreal region relative to central and southern Alberta. Enteric fermentation is mainly associated with cattle in Alberta (Environment Canada 2010), and cattle density for census subdivisions within the study area (0.385 cattle/ha of improved agricultural land) is only 79% relative to that of Alberta (0.490 cattle/ha). Manure management emissions are largely associated with cattle and pigs (Environment Canada 2010), and the combined cattle and pig density for census subdivisions within the study area (0.430/ha) is only 66.4% relative to that of Alberta (0.647/ha) (Statistics Canada 2006a). The lower livestock densities were accounted for by reducing emission coefficients for enteric fermentation from 0.6744 to 0.531 tCO_2e/ha, and for manure management from 0.1756 to 0.117 tCO_2e/ha. The combined (i.e., enteric fermentation, manure management, and agriculture soils) agricultural GHG emission intensity for the study area was therefore estimated to be 1.263 tCO_2e/ha of improved agricultural land.

4.9.2 Sulphur and Nitrogen Oxide Emissions

Sulphur and nitrous oxide emission intensities (Table 12) were based on national emissions in 2009[61] as reported by the National Pollutant Release Inventory (http://www.ec.gc.ca/inrp-npri/default.asp?lang=En&n=4A577BB9-1). Agriculture is not associated with sulphur and nitrogen oxide emissions according to the inventory. Forestry sector emissions (i.e., Pulp and Paper Industry and Wood Industry) were 31,284 tonnes of sulphur oxides (tSO_x) and 40,754 tonnes of nitrous oxides (tNO_x). That same year, total roundwood production in Canada was 118,524,000 m^3, resulting in emission intensities of 2.65e-04 tSO_x/m^3 and 3.45e-04 tNO_x/m^3. Upstream petroleum industry emissions included 135,798 tSO_x and 363,905 tNO_x from crude oil and natural gas production and processing, 14,062 tSO_x and 12,494 tNO_x from oil sands in-situ extraction and processing, 10,572 tSO_x and 2,984 tNO_x from oil sands mining extraction and processing, and 107,640 tSO_x and 27,044 tNO_x from upgrading[62]. Crude oil and natural gas emissions were divided between conventional oil and natural gas production based on the relative abundance of emissions associated with the light/medium oil sector versus gas production and processing sectors in 2000[63]. For bitumen production, 60% of the upgrading emissions were included based on the assumption that 60% of upgrading in Alberta is likely to occur at onsite upgraders

---

[61] Although emissions are available from 1985 to 2009, coefficients are based on 2009 to ensure that recent technologies that reduce emission intensities are accounted for.

[62] Not included here are "other upstream petroleum industry" emissions (27,015 tSO_x and 4,866 tNO_x), as well as "Downstream Petroleum Industry" emissions (71,050 tSO_x and 24,123 tNO_x).

[63] Gas production and processing accounts for far more SO_x and NO_x emissions than does the light/medium oil sector; in the year 2000, SO_x and NO_x emissions from the light/medium oil sector were 6.8% and 0.6% of that from the gas production and processing sectors.

(Griffiths and Dyer 2008). Emissions for conventional oil, gas, in-situ bitumen, and mining bitumen production were combined with 2009 production data (CAPP 2011) to derive emission coefficients[64].

Table 12. GHG, SOx, and NOx emission coefficients.

	GHG emissions (tCO_2e)	SO_x emissions (t)	NO_x emissions (t)
Agriculture (per ha improved agricultural land)	1.263	0	0
Forestry (per m^3)	0.150	2.646-04	3.446e-04
Conventional oil (per m^3)	0.222	1.218e-04	2.838e-05
In-situ bitumen (per m^3)	0.471	1.261e-03	5.881e-04
Surface bitumen (per m^3)	0.329	1.075e-03	2.775e-04
Conventional gas (per m^3)	1.029e-04	6.973e-07	1.984e-06
Shale gas (per m^3)	1.666e-04	6.973e-07	1.984e-06

4.10 Biotic Carbon

Biotic carbon was assessed for upland forest ecosystems. Insufficient information was available to assess the response of peatland carbon to land use.

4.10.1 Forest Carbon

The response of forest carbon to changes in landscape composition was assessed using relationships derived from sensitivity analyses conducted in the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; Kull et al. 2007). The model is widely used in Canada, to inform both national and operational forest carbon accounting (Kurz et al. 2009). The Carbon Budget Model of the Canadian Forest Sector assesses biomass and dead organic matter (DOM) pools, and simulates changes to the pools in response to succession, forestry, deforestation, afforestation, and natural disturbances. A system of equations derived from the literature and tree measurements are applied by the model to convert growth and yield data to biomass components. DOM dynamics are simulated by applying model parameters based on a stand's stage of development and its disturbance and management history.

The intent in applying CBM-CFS3 to parameterize carbon relationships in ALCES was to combine CBM-CFS3's carbon modeling and ALCES's land use modeling capacities. The approach was to conduct simulations in CBM-CFS3 to approximate relationships between land cover type/age and carbon storage. These relationships were then applied in ALCES to estimate biomass and DOM carbon associated with simulated landscapes.

[64] Upstream emissions in 2009 are estimated to equal 8,596 tSO_x and 2,003 tNO_x for conventional oil production; 127,202 tSO_x and 361,902 tNO_x for gas production; 41,688 tSO_x and 19,435 tNO_x for in-situ bitumen production; and 47,529 tSO_x and 12,269 tNO_x for surface bitumen production (upgrading emissions were divided between in-situ bitumen and mining relative to their production in 2009). Hydrocarbon production that same year was 70,568,357 m^3 conventional oil, 1,8243e11 natural gas, 33,047,000 m^3 in-situ bitumen, and 44,209,000 m^3 surface bitumen. The resulting emission intensity estimates for the bitumen sector are less than CAPP's (2010) estimates of 0.0016 tSO_2/m^3 bitumen and 0.00084 tNO_x/m^3 bitumen. The lower emission intensity estimates is in part because emissions from offsite upgrading is not included.

Application of CMB-CFS3 required growth and yield data, as well as specification of ecozone, jurisdiction, and forest species. Settings for ecozone and jurisdiction were the Boreal Plains and Alberta, respectively, given that Alberta's Boreal Plains accounts for a larger percent of the study area (49%) than any other combination of ecozone and jurisdiction[65]. The leading species for softwood and hardwood forest types were spruce and poplar, respectively. Spruce and poplar are the most abundant stocked coniferous and deciduous forest types in Alberta (Power and Gillis 2001). As discussed previously, growth and yield data were from the Alberta Pacific Forest Management Agreement area (Appendix 6.2).

To derive carbon relationships for use in ALCES, CBM-CFS3 was applied to assess biomass and DOM carbon stocks across 10 seral stages for each cover type. Figure 16 shows the relationship between forest age and carbon for spruce forest. Of note is that the relationship between forest age and DOM carbon (but not biomass carbon) differed depending on whether the last disturbance was timber harvest, fire, or footprint, although the difference diminishes as time since disturbance increases. The relationship was also influenced by the age of the forest prior to the last disturbance (Figure 17), because stands of different ages vary in terms of the volume of carbon within DOM pools upon disturbance. Again, the difference diminishes as time since disturbance increases. To incorporate the influence of a forest's history on carbon stores, CBM-CFS3 simulations explored 41 scenarios for each forest type to incorporate 3 origins (fire, harvest, and footprint reclamation[66]) and a range of pre-disturbance or pre-reclamation ages (10, 20, …, 180 years[67]). Disturbances prior to the most recent disturbance also influence a forest's DOM trajectory but to a lesser extent (Figure 18), and were therefore not incorporated in DOM carbon relationships.

Output from the CBM-CFS3 simulations were used to fit carbon relationships for each of the ten seral stages tracked by ALCES. For biomass carbon, the relationship consisted of a single carbon value because CBM-CFS3 simulations indicated that biomass carbon storage is not affected by a stand's history (i.e., past disturbance type and stand age prior to disturbance). DOM carbon, however, required a more sophisticated set of relationships to incorporate the effects of the forest's origin and the pre-disturbance or pre-reclamation age (Figure 19). Appendix 6.3.5 presents the carbon relationships, derived from CBM-CFS3, that were applied in ALCES simulations. For a given forest type and seral stage, ALCES applied one or more of the three types of DOM relationships (fire, harvest, and footprint origin)

---

[65] Due to the large size of the study area, the mean annual temperature exhibits substantial range (approximately 6 C) across the study area. Temperature is influential on DOM carbon, and a sensitivity analysis based on 80 year old spruce forest determined that DOM carbon varies by approximately ±10% across the temperature range exhibited in the study area. However, the general shape of the relationship between DOM and stand age is insensitive to temperature. As such, the DOM carbon estimate from the scenario analysis should be viewed as approximate, but the shape of the response of DOM carbon to land use simulations (i.e., due to changes in forest age) is likely to be robust.

[66] Simulation of carbon accumulation following reclamation from forest required specification of initial DOM carbon in the footprint prior to reforestation. Footprint DOM carbon was based on a CBM-CFS3 simulation that tracked DOM carbon pools following the conversion of 80-year old forest to oil and gas footprint (with salvage and decay). DOM carbon for footprint of age *x* was based on the status of DOM carbon pools *x* years following conversion of the 80-year old forest to footprint.

[67] For harvest origin forest, the range of pre-harvest forest age was limited to 60, 70, …, 180 years because the minimum harvest age in the simulations is 60 years. For footprint origin forest, the range of pre-reclamation footprint age was limited to 10, 20, …, 100 years because footprint ages do not typically exceed 100 years.

based on the proportion of the area in the seral stage that originated from each disturbance type[68]. The average pre-disturbance or pre-reclamation age required by the relationships was calculated in ALCES as a weighted average of the pre-disturbance age over the past 50 years[69], with the weights reflecting the diminishing influence of less recent simulation years on DOM (Figure 20 and Appendix 6.3.5).

Deforestation to create industrial footprints (roads, wells, etc.) affects carbon both through the clearing of vegetation (i.e., decrease in biotic carbon and increase in DOM carbon) and its subsequent decomposition. A series of simulations were completed in CBM-CFS3 to estimate a DOM carbon trajectory (i.e., over time) for footprint (Figure 21) and the influence of pre-disturbance forest age on the trajectory (Figure 22). Across a range of plausible average forest ages for the region (40-120 years), the trajectory was relatively insensitive (~±3 tonnes/ha) to the forest age prior to clearing for footprint. As a result, forest age prior to deforestation was not incorporated when modelling footprint carbon dynamics in ALCES. Instead, the DOM trajectory for clearing of 80-year old forest was used (Appendix 6.3.5).

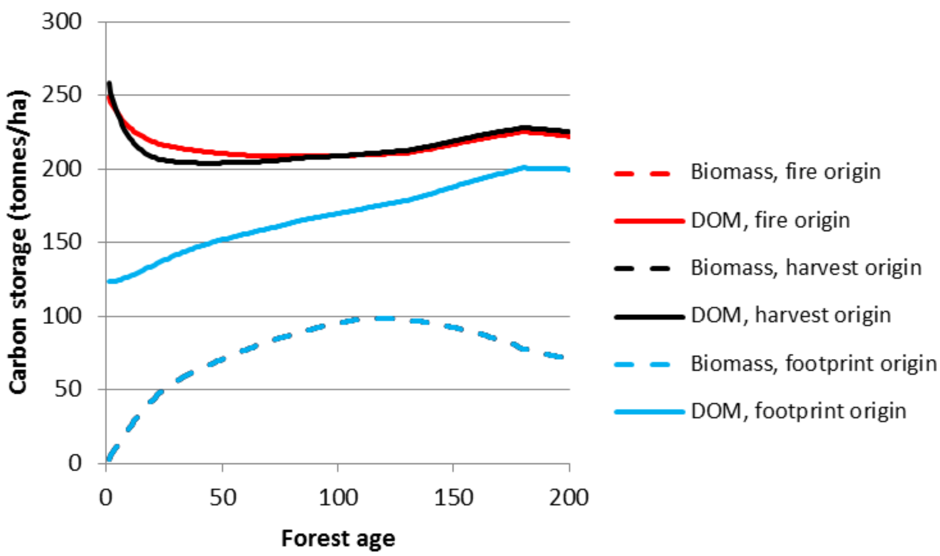


Figure 16. Biomass and DOM carbon accumulation trajectories (i.e., carbon by forest age) for spruce forest of fire, harvest, and footprint origin[70]. Based on CBM-CFS3 simulations. A curve for biomass accumulation of fire and harvest origin forest does not appear because it is identical to footprint origin biomass accumulation.

---

[68] The initial area of harvest origin-forest is assumed to be 60,000 ha, with the remaining forest being fire-origin. The 60,000 ha estimate is based on the proportion of Alberta's tenured forests that have been harvested over the past rotation (80 years). Between 1930 and 2009, 2.3 million ha of forest was harvested in Alberta's 27 million ha's of tenured forests. Therefore, about 9% of Alberta's tenured forest has been harvested. If the level of harvest intensity was similar in the study area to that in Alberta over the past rotation, then approximately 9% of the study area's 41,421,260 ha of tenured forest have been harvested (i.e., 3,727,913 ha).
[69] Pre-disturbance age for the 50 years prior to the start of the simulation will be assumed to equal the average age of the forest type at the start of the simulation.
[70] Forest or footprint age prior to disturbance or footprint reclamation was 100 years.

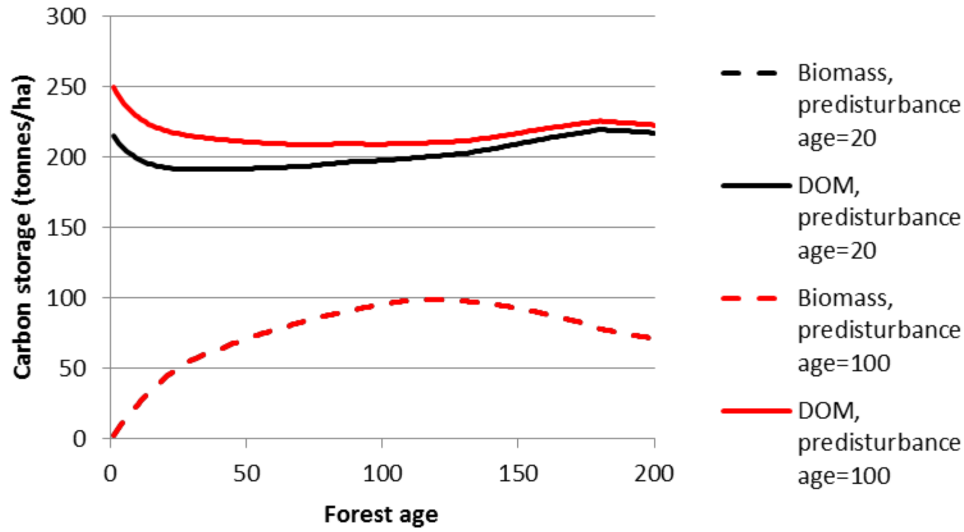


Figure 17. Biomass and DOM carbon accumulation trajectories (i.e., carbon by forest age) for spruce forest following the burning of forest with pre-disturbance ages of 20 and 100 years. Based on CBM-CFS3 simulations. A biomass accumulation curve does not appear for forest with a pre-disturbance age of 20 years because it is identical to the curve for forest with a pre-disturbance age of 100 years.

Figure 18. DOM carbon accumulation trajectories (i.e., carbon by stand age) for poplar stands with different disturbance histories, demonstrating that the age of the stand prior to the most recent disturbance (i.e., previous fire) is more influential to DOM carbon than the age of the stand prior to the second most recent disturbance (i.e., 2nd previous fire). Based on CBM-CFS3 simulations.

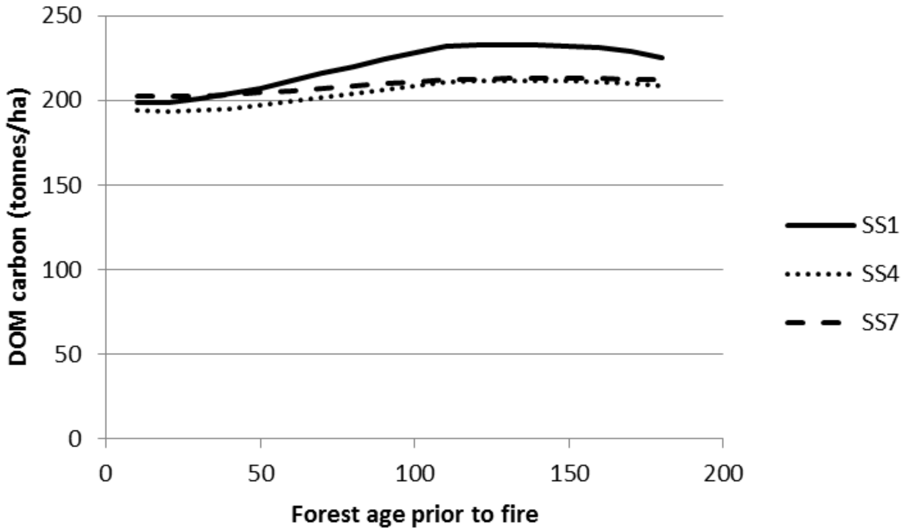


Figure 19. Spruce DOM carbon following fire for three seral stages (SS1, SS4, and SS7). DOM carbon for each seral stage is influenced by the age of the previous forest prior to fire.

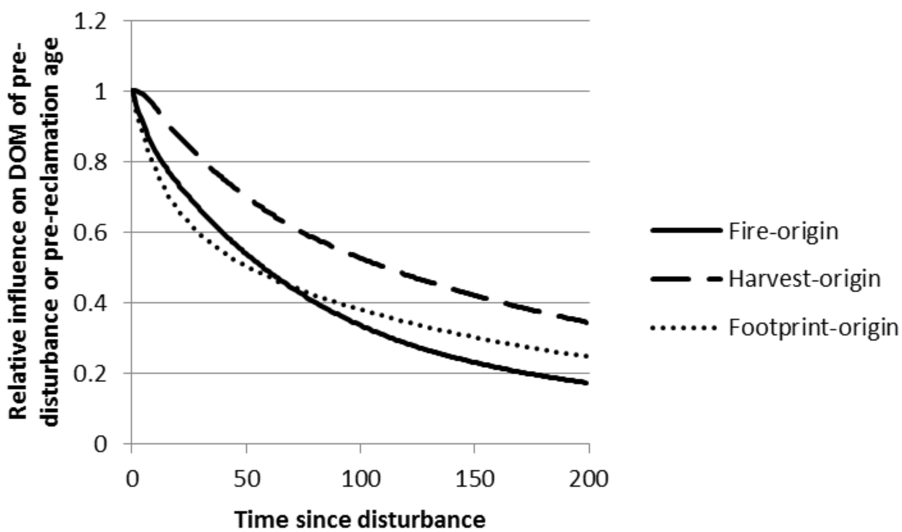


Figure 20. The decreasing influence with time since disturbance of pre-disturbance age on DOM carbon. Influence on DOM carbon calculated as the difference between the largest and smallest DOM carbon for a given stand age (i.e., across pre-disturbance ages). Relative influence calculated as the influence of stand age on DOM for a given time since disturbance divided by the influence immediately following disturbance.

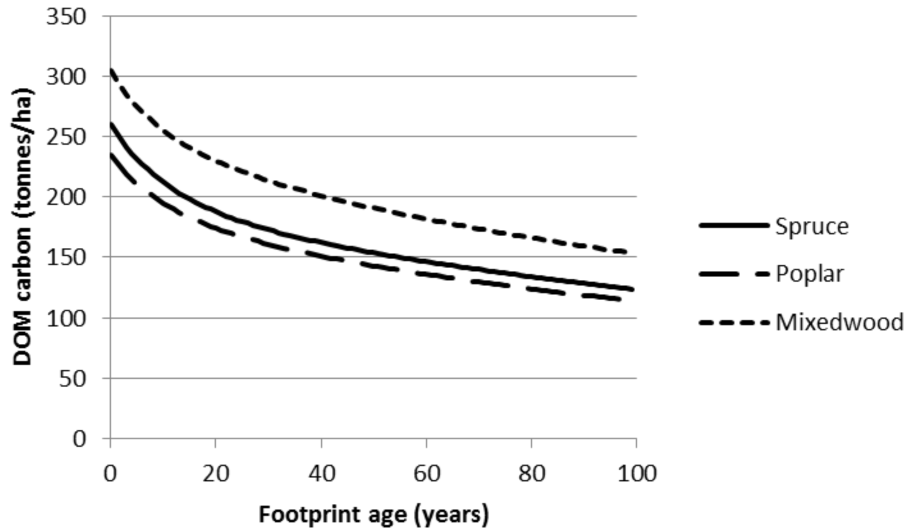


Figure 21. DOM carbon trajectory in response to clearing of forest for oil and gas footprint (with salvage). Forest age prior to clearing was 80 years.

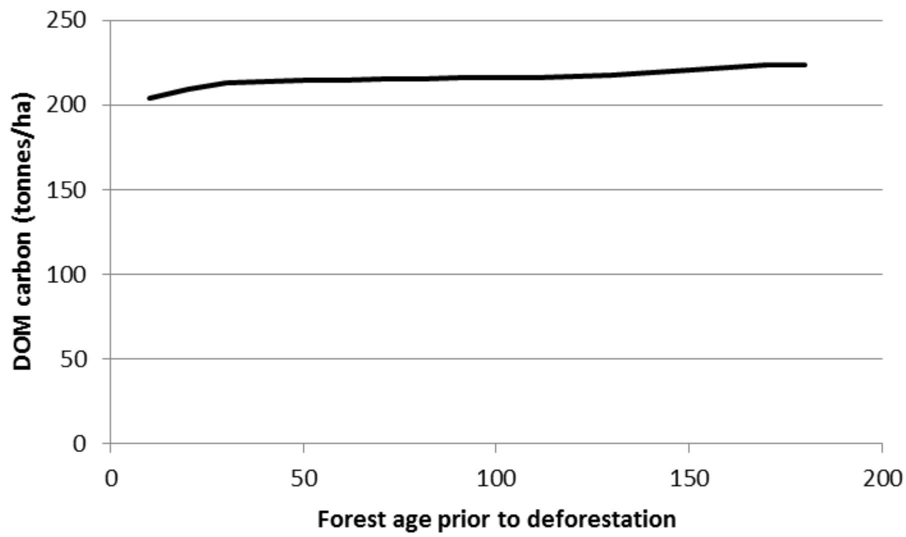


Figure 22. Influence of spruce forest age prior to deforestation on DOM carbon for 10-year old oil and gas footprint.

4.11 Gross Domestic Product and Employment

Coefficients relating GDP and employment to land use were derived by relating Alberta industry performance by sector between 2000 and 2007 (PriceWaterhouseCoopers 2009) to provincial annual timber production (Canadian Council of Forest Ministers 2011), petroleum production and revenue (CAPP 2011), and agricultural land use (Statistics Canada 2001a, 2006a).

Between 2000 and 2007, average annual GDP and employment attributable to forest products were \$1412 million and 10,925 jobs, respectively. Over this same period, average annual timber production was 21,801,251 m^3. Therefore, each m^3 of timber production was associated with \$64.76 of GDP and 0.000501 jobs.

Data for agricultural land use were only available for 2001 and 2006, the years of Statistics Canada's agricultural census. During these years, the average area of improved land (i.e., land in crops, summerfallow, and tame or seeded pasture) was 13,103,160 ha. GDP and employment from primary agriculture during these years was $4064 million and 54,500 jobs, respectively. Therefore, each ha of improved land was associated with $310.12 GDP and 0.004157 jobs.

To derive GDP and employment data by hydrocarbon type (gas, conventional oil, and bitumen), GDP and employment data for the oil and gas extraction and energy services[71] sectors between 2000 and 2007 were apportioned based on the distribution of gross revenue among the three hydrocarbon types. Estimated average annual GDP was $18,341 million, $6,500 million, and 8,543 million from gas, conventional oil, and bitumen production, respectively. Estimated average annual employment associated with each hydrocarbon type was 57,293, 20,122, and 27,935. Over the same time period, average annual hydrocarbon production was 137,381 billion m^3 gas, 36,255,463 m^3 conventional oil, and 52,137,867 m^3 bitumen. Therefore, GDP rates were estimated at $0.1335/$m^3$ gas, $179.29/$m^3$ conventional oil, and $163.86/$m^3$ bitumen. Employment rates were estimated at 4.17e-07/m^3 gas, 5.55e-04/m^3 conventional oil, and 5.35e-04/m^3 bitumen.

The approach of deriving GDP and employment coefficients from a sector's performance between 2000 and 2007 is accompanied by implicit assumptions that deserve mention. First, the approach assumes a fixed relationship between resource production (e.g., timber harvest) and economic performance (e.g., GDP, employment), and that factors such as prices, wages, and technology are not important. In the case of agriculture, an additional assumption is that the amount of production derived per unit of arable land is also fixed. Further, because the performance of each sector is assessed independently, the approach assumes that interdependence between sectors is not important. In reality, interdependency among sectors exists and the relationship between inputs and outputs will change through time. The economic coefficients are therefore simplifications of reality and should be considered approximations of the economic influence of each sector rather than a comprehensive assessment.

A more sophisticated approach to modeling economic performance would be input output analysis, which incorporates interdependence between sectors (but not potential changes in the relationships between inputs, outputs, and GDP or employment). Input output analysis was not applied because a model that incorporated all sectors was not available and development of such a model was beyond project scope. Although relevant input output models exist for at least some sectors, the various models differ with respect to the assumptions applied. In contrast, an advantage of deriving economic coefficients from past employment and GDP is that assumptions applied to each sector were consistent.

To assess the potential discrepancy between the approach used and input output analysis, economic coefficients were derived from the results of an input output analysis of the oil sands industry (Timilsina et al. 2005), the dominant sector in the region. Averaged over a 20-year projection, the input output analysis estimated a direct oil sector GDP impact of $163.65/$m^3$ and direct employment impact of 4.22e-04 person years/m^3. The comparison suggests that, at least for the dominant sector of the regional economy, the coefficients derived for the simulation (Table 13) are similar to direct economic impacts assessed by an input output model (equivalent for GDP and 25% higher for employment). However, the

[71] The energy services sector provides support to primary oil and gas producers (e.g., drilling, well maintenance, etc.).

input output analysis also assesses impacts of oil sands production to a wide range of other sectors, from forestry to manufacturing to health care. These indirect impacts were equivalent to 57% and 250% of the direct GDP and employment impacts. It is important to realize, therefore, that the direct economic performance reflected by the GDP and employment coefficients (Table 13) substantially under represent the full impact of resource production on the economy. Limiting the economic indicators to direct impacts is consistent with the approach applied to ecological indicators, where impacts were limited to those occurring within the study area. Indirect economic impacts may occur outside of the study area, such as the manufacturing of equipment needed for natural resource production. An example of limiting the assessment of ecological impacts to those that occur within the study area is the exclusion of emissions that are associated with offsite (e.g., Edmonton) bitumen upgrading and the consumption of fuel produced from bitumen (e.g., vehicle exhaust).

Table 13. GDP and employment coefficients by resource sector.

Land use	GDP	Employment
Timber production	$\$64.76/m^3$	$0.000501/m^3$
Agriculture	$310.12/ha improved land	0.004157/ha
Gas	$\$0.1335/m^3$	4.17e-07/ m^3
Conventional oil	\$179.29/ m^3	5.55e-04/ m^3
Bitumen	\$163.86/ m^3	5.35e-04/ m^3

5 Mapping Possible Future Landscape Outcomes

Maps of potential future landscape composition were created in ALCES Mapper® by distributing simulated annual footprint creation and reclamation across the study area based on available spatial information (listed below). In a given simulation year, the amount of each footprint type created within each landscape type was equivalent to that simulated by ALCES®[72]. Under the conservation zoning scenarios, new footprints were not allowed within conservation areas. To avoid excessive aggregation of simulated footprint, the amount of a given footprint type within each 25 km^2 cell was not allowed to exceed the 90th percentile of the current distribution of the amount of the footprint type per cell. The location of the new footprint was random but guided by the availability of resources[73], as follows:

- hydrocarbon sector footprints (i.e., seismic, wells, pipelines, roads, industrial plants) were distributed based on the location (m^3/ha) of reserves, the production rate for each hydrocarbon type in a given simulation year, and the intensity of footprint associated with a given hydrocarbon type. For example, the location of seismic footprint shifted during a simulation towards areas with unconventional reserves as production of conventional oil and natural gas declined.
- forestry footprints (cutblocks, roads) were distributed across tenures based on their annual allowable cut. Timber harvest was assumed to disturb all merchantable forest within a selected cell, to avoid excessive dispersion of cutblocks.
- agriculture footprints (farmland, roads) were distributed across arable land[74] based on the amount of agricultural expansion expected within each jurisdiction's portion of the study area (see supplemental methods)
- settlements were expanded contagiously from existing settlement footprint

---

[72] The distribution of new footprint across land cover types in ALCES was based on the composition of those portions of the study area with unprotected resource potential.

[73] Each cell is associated with a value, referred to as the mask value, that expresses its relative likelihood of receiving a given footprint type, given the relative abundance of related resource types. When selecting the next cell to grow footprint in, Mapper randomly selects a cell from the available list (i.e., unprotected cells with footprint below the maximum footprint threshold). Mapper then generates a random number between 0 and the 90th percentile of mask values across cells with non-zero mask values. If the random number is less than the selected cell's mask value, then the cell receives footprint. Otherwise, the cell does not receive footprint during that year. This selection process distributes footprint across cells randomly but relative to the distribution of relevant resources.

[74] The location of arable land was based on classes 1-3 from the Canada Land Inventory's agriculture layer (http://geogratis.cgdi.gc.ca/cgi-bin/geogratis/cli/agriculture.pl). Classes 1-3 are judged capable of supporting crop production (Canada Land Inventory 1976)

- rural residential footprint occurred within agricultural areas and in proximity to settlements, based on the current distribution of rural residences relative to these features[75]

The spatial distribution of footprint reclamation was based on the age of footprint (i.e., oldest first). The only age information available for existing footprint was the drilling year for wells, therefore all existing non-permanent footprint within a cell was assumed to have the same age as wells within that cell. Exceptions to the oldest-first reclamation pattern were made to more accurately represent the lifespan of footprint in certain situations. Seismic footprint outside the boundaries of hydrocarbon reserves was assumed to be conventional seismic and therefore have an average lifespan of 60 years (Lee and Boutin 2006). For example, reclamation of seismic footprint located outside of hydrocarbon reserves was randomly distributed spatially but at a rate that would result in complete reclamation after 60 years. Pipeline footprint outside of hydrocarbon reserves was assumed to be part of the permanent distribution network, rather than segments to individual wells.

[75] 66% of existing rural residences are located in agricultural areas. The majority (88%) of the remaining rural residences occur within 25 km of a settlement. Simulations assumed that 66% of new rural residences will occur in agricultural areas and that the remaining rural residences will occur within 25 km of settlements.

6 Appendices

6.1 Forest age-class composition

Table 14. Estimated area within each seral stage for forested cover types.

	Coniferous forest		Deciduous forest		Mixedwood forest	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
0-20	1,795,268	7.9	680,546	5.0	174,418	7.8
21-40	3,983,410	17.6	1,362,602	9.9	325,389	14.5
41-60	2,069,961	9.2	2,066,353	15.0	293,565	13.0
61-80	2,609,620	11.5	2,609,380	19.0	304,682	13.5
81-100	2,891,731	12.8	2,000,684	14.5	331,537	14.7
101-120	4,228,796	18.7	2,187,815	15.9	414,355	18.4
121-140	2,850,478	12.6	1,657,554	12.1	254,779	11.3
141-160	1,391,956	6.2	816,646	5.9	102,091	4.5
161-180	681,634	3.0	330,514	2.4	43,551	1.9
180+	106,872	0.5	47,652	0.4	7,333	0.3

6.2 Forest Growth and Yield Tables

Growth and yield curves for each of the coniferous, deciduous, and mixedwood forest types were estimated as area-weighted averages of yield curves for coniferous leading, deciduous leading, and mixed forest types, respectively, as reported in the Al-Pac detailed forest management plan (Alberta-Pacific Forest Industries Inc. 2008).

Table 15. Growth and yield tables for coniferous, deciduous, and mixedwood forest.

	Coniferous forest		Deciduous forest		Mixedwood forest	
Age-class (years)	Softwood volume (m^3/ha)	Hardwood volume (m^3/ha)	Softwood volume (m^3/ha)	Hardwood volume (m^3/ha)	Softwood volume (m^3/ha)	Hardwood volume (m^3/ha)
0-20	2.13	0.45	0.41	4.33	2.23	2.77
21-40	22.82	4.45	5.58	43.41	20.56	26.23
41-60	58.12	11.69	14.82	102.54	48.84	61.32
61-80	97.37	20.12	25.17	157.34	78.02	95.12
81-100	133.2	27.98	33.76	196.40	103.07	121.28
101-120	161.67	32.54	39.31	213.28	121.93	134.59
121-140	162.38	27.61	41.20	187.43	127.12	118.28
141-160	147.19	17.37	38.69	118.63	119.03	74.87
161-180	124.27	6.10	33.71	38.25	102.98	24.14
181-200	100.88	0.11	28.37	0	84.76	0

6.3 Parameter values for indicator models

6.3.1 Moose HSI

Table 16. Habitat value by cover or footprint type for the moose HSI model. Values are based on a HSI model developed for CEMA and revised through the LARP process.

Cover or footprint type	Corresponding class from model developed for CEMA/LARP	Value
Deciduous	Hardwood	0.93
Mixedwood	Mixedwood	0.7
Coniferous	White spruce, Pine (weighted average[76])	0.49
Shrub	Shrub tall, Shrub low	0.7
Bryoids	Open black spruce lichen moss	0.2
Herbaceous	Native herbaceous	0.5
Treed peatland	Open black spruce fen, Close black spruce fen (average)	0.5
Shrub peatland	Open black spruce fen	0.6
Herbaceous peatland	Bog	0.2
Barren	Beach, dune	0
Water	Lotic, Lentic	0.2
Annual cropland	Cultivated crop	0
Forage cropland	Forage crop	0
Road	Minor road	0.4
Inblock road	Inblock road	0.6
Transmission line	Transmission line	0.5
Seismic line	Seismic line	0.6
Wellsite	Wellsite	0.1

Table 17. The width of buffers placed around industrial footprints, and percent use of habitat within the buffers. High (i.e., protection) and moderate (i.e., best practices) access management strategies are implemented by multiplying buffer width by 0 and 0.15, respectively.

Footprint type	Buffer width (m)	Buffer use
Road and rail	100	0.25
Inblock road	50	0.9
Transmission corridor	100	0.5
Pipeline	100	0.5
Seismic	200	0.5
Wellsite	100	0.5
Industrial plant	200	0.25
Oilsands mine	200	0.25
Gravel pits	200	0.25
Settlements	500	0.5

[76] The original HSI model included separate values for white spruce (0.55) and pine (0.4). These values were combined as a weighted average to estimate a softwood value, with weights based on the relative area of stocked spruce (7,047,090 ha) and pine (5,220,500 ha) forest in Alberta (Power and Gillis 2006).

Rural residential/camp	500	0.5

Table 18. Habitat quality by age class for moose.

Forest age class	Habitat quality
0-20	1
21-40	1
41-60	0.9
61-80	0.4
81-100	0.2
101-120	0.1
121-140	0.1
141-160	0.2
161-180	0.3
>180	0.6

6.3.2 Fisher HSI

Table 19. Habitat value by cover or footprint type for the fisher HSI model. Values are based on a HSI model developed for CEMA.

Cover type	Corresponding class from model developed for CEMA/LARP	Value
Hardwood	Hardwood	0
Mixedwood	Mixedwood	1
Softwood	White spruce, Pine (weighted average[77])	0.61
Shrub tall	Shrub tall	0
Shrub low	Shrub low	0
Bryoids	Open black spruce lichen moss	0
Herbaceous	Native herbaceous	0
Grassland	Native herbaceous	0
Treed peatland	Open black spruce fen, Close black spruce fen (average)	0.05
Shrub peatland	Open black spruce fen	0
Herbaceous peatland	Bog	0
Barren	Beach Dune	0
Water	Lotic, Lentic	0
Annual cropland	Cultivated crop	0
Forage cropland	Forage crop	0

[77] The original HSI model included separate values for white spruce (1) and pine (0.1). These values were combined as a weighted average to estimate a softwood value, with weights based on the relative area of stocked spruce (7,047,090 ha) and pine (5,220,500 ha) forest in Alberta (Power and Gillis 2006).

Table 20. The width of buffers placed around industrial footprints, and percent use of habitat within the buffers by fisher with and without access management.

Footprint type	Buffer width (m)	Buffer use
Major road	100	0.1
Minor road	100	0.1
Inblock road	100	0.1
Transmission corridor	100	0.1
Pipeline	100	0.1
Seismic	100	0.1
Wellsite	100	0.1
Industrial plant	100	0.1
Oilsands mine	100	0.1
Gravel pits	100	0.1
Settlements	100	0.1
Rural residential/camp	100	0.1

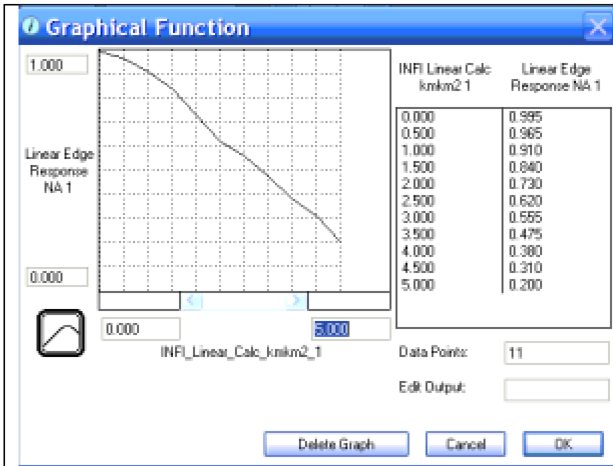
Table 21. Habitat quality by age class for fisher.

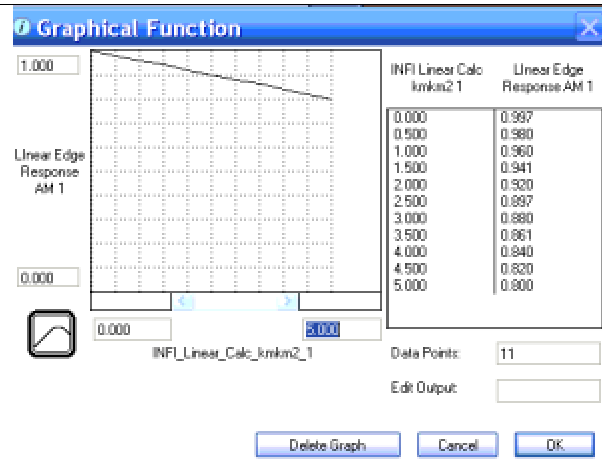
Forest age class	Habitat quality
0-20	0
21-40	0
41-60	0.4
61-80	0.7
81-100	1
101-120	1
121-140	1
141-160	1
161-180	1
>180	1

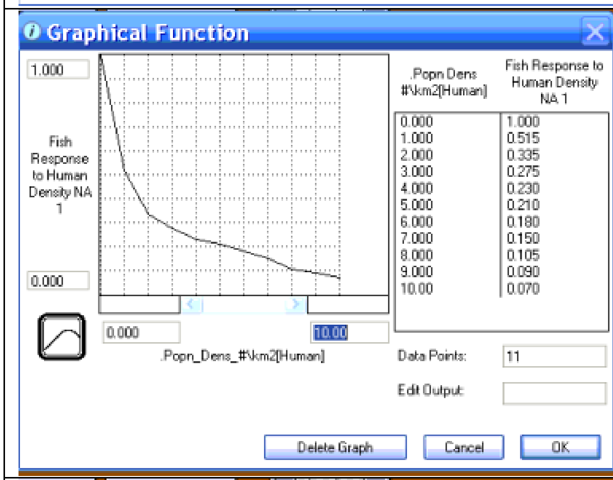
6.3.3 Index of Native Fish Integrity

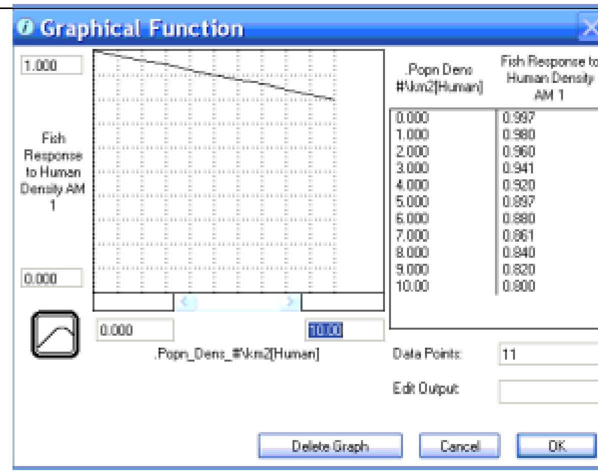
Table 22. Relationships between INFI and risk factors (linear edge density, population density, stream flow, and watershed discontinutiy with and without access management.

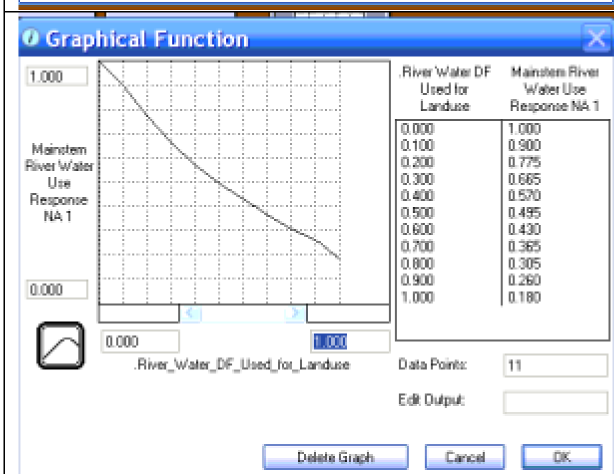
No access management	Access management

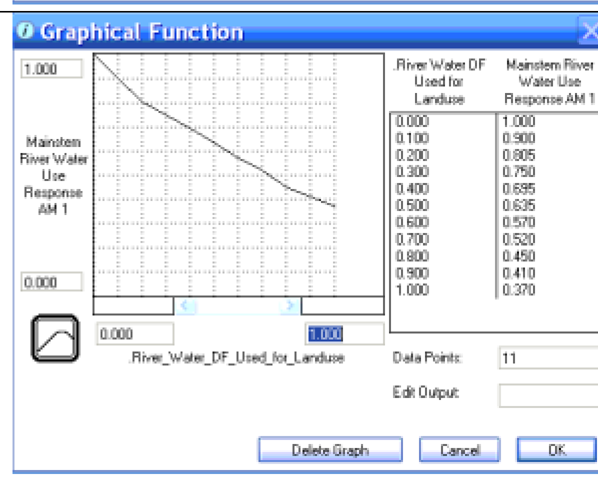

Graphical Function
1.000
Linear Edge Response NA 1
0.000
0.000
5.000
INFI_Linear_Calc_kmkm2_1
INFI Linear Calc kmkm2 1
Linear Edge Response NA 1
0.000 0.995
0.500 0.965
1.000 0.910
1.500 0.840
2.000 0.730
2.500 0.620
3.000 0.555
3.500 0.475
4.000 0.380
4.500 0.310
5.000 0.200
Data Points: 11
Edit Output:
Delete Graph
Cancel
OK

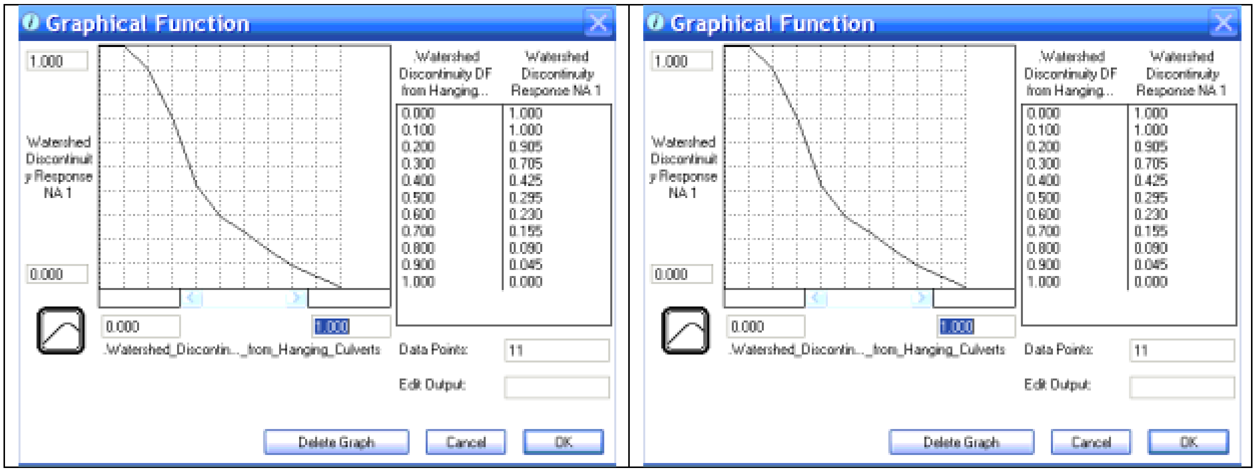

Graphical Function
1.000
Linear Edge Response AM 1
0.000
0.000
5.000
INFI_Linear_Calc_kmkm2_1
INFI Linear Calc kmkm2 1
Linear Edge Response AM 1
0.000 0.997
0.500 0.980
1.000 0.960
1.500 0.941
2.000 0.920
2.500 0.897
3.000 0.880
3.500 0.861
4.000 0.840
4.500 0.820
5.000 0.800
Data Points: 11
Edit Output:
Delete Graph
Cancel
OK


Graphical Function
1.000
Fish Response to Human Density NA 1
0.000
0.000
10.00
.Popn_Dens_#\km2[Human]
.Popn Dens #\km2[Human]
Fish Response to Human Density NA 1
0.000 1.000
1.000 0.515
2.000 0.335
3.000 0.275
4.000 0.230
5.000 0.210
6.000 0.180
7.000 0.150
8.000 0.105
9.000 0.090
10.00 0.070
Data Points: 11
Edit Output:
Delete Graph
Cancel
OK


Graphical Function
1.000
Fish Response to Human Density AM 1
0.000
0.000
10.00
.Popn_Dens_#\km2[Human]
.Popn Dens #\km2[Human]
Fish Response to Human Density AM 1
0.000 0.997
1.000 0.980
2.000 0.960
3.000 0.941
4.000 0.920
5.000 0.897
6.000 0.880
7.000 0.861
8.000 0.840
9.000 0.820
10.00 0.800
Data Points: 11
Edit Output:
Delete Graph
Cancel
OK


Graphical Function
1.000
Mainstem River Water Use Response NA 1
0.000
0.000
1.000
.River_Water_DF_Used_for_Landuse
.River Water DF Used for Landuse
Mainstem River Water Use Response NA 1
0.000 1.000
0.100 0.900
0.200 0.775
0.300 0.665
0.400 0.570
0.500 0.495
0.600 0.430
0.700 0.365
0.800 0.305
0.900 0.260
1.000 0.180
Data Points: 11
Edit Output:
Delete Graph
Cancel
OK


Graphical Function
1.000
Mainstem River Water Use Response AM 1
0.000
0.000
1.000
.River_Water_DF_Used_for_Landuse
.River Water DF Used for Landuse
Mainstem River Water Use Response AM 1
0.000 1.000
0.100 0.900
0.200 0.805
0.300 0.750
0.400 0.695
0.500 0.635
0.600 0.570
0.700 0.520
0.800 0.450
0.900 0.410
1.000 0.370
Data Points: 11
Edit Output:
Delete Graph
Cancel
OK



6.3.4 Water Quality

Table 23. Coefficients for assessing phosphorus and nitrogen runoff associated with simulated landscapes.

Land cover type	**Phosphorus**	**Nitrogen**
	Runoff (kg/ha/year)	Runoff (kg/ha/year)
Deciduous forest	0.288	1.597
Coniferous forest	0.288	1.597
Mixedwood forest	0.288	1.597
Shrub	0.392	2.172
Bryoids	0.044	0.203
Herbaceous	0.044	0.203
Grassland	0.044	0.203
Treed peatland	0	0
Shrub peatland	0	0
Herbaceous peatland	0	0
Barren	0.2	2.95
Water	0	0
Annual cropland	0.452	5.255
Forage cropland	0.452	5.255
Major road	1.473	46.078
Minor road	5.677	6.754
Inblock road	5.677	6.754
Transmission corridor	0.63	1.622
Pipeline	0.944	2.433
Seismic	0.472	1.216
Well site	3.232	6.416
Industrial plant	0.865	6.686

Oilsands mine	0.317	2.49
Gravel pits	0.317	2.49
Settlements	0.836	6.732
Rural residential/camp	0.122	1.482

6.3.5 Forest Carbon

Table 24. Relationship between carbon and spruce forest age. DOM carbon density is expressed as an equation where x refers to the age of the forest prior to the last fire (fire origin) or harvest (harvest origin), or the footprint age prior to reclamation (footprint origin).

Forest age (years)	Biotic carbon (tonne/ha)	Relationship for DOM carbon tonne/ha (and R^2)		
		Fire origin	Harvest origin	Footprint origin
0-20	24.3	$2E\text{-}07x^4 - 9E\text{-}05x^3 + 0.0137x^2 - 0.3388x + 200.6$ $R^2 = 0.9991$	$0.0017x^2 - 0.2949x + 234.28$ $R^2 = 0.9812$	$0.0052x^2 - 1.3165x + 207.96$ $R^2 = 0.9962$
21-40	55.6	$2E\text{-}07x^4 - 0.0001x^3 + 0.015x^2 - 0.5051x + 196.1$ $R^2 = 0.9991$	$0.0012x^2 - 0.186x + 211.76$ $R^2 = 0.9896$	$0.0024x^2 - 0.8438x + 202.23$ $R^2 = 0.9995$
41-60	70.8	$2E\text{-}07x^4 - 8E\text{-}05x^3 + 0.0126x^2 - 0.436x + 196.01$ $R^2 = 0.9992$	$0.0008x^2 - 0.1129x + 207.24$ $R^2 = 0.9925$	$0.0016x^2 - 0.6699x + 203.26$ $R^2 = 0.9999$
61-80	82.7	$1E\text{-}07x^4 - 7E\text{-}05x^3 + 0.0098x^2 - 0.3335x + 196.52$ $R^2 = 0.9993$	$0.0006x^2 - 0.066x + 206.04$ $R^2 = 0.9941$	$0.0012x^2 - 0.5729x + 204.66$ $R^2 = 0.9999$
81-100	91.7	$1E\text{-}07x^4 - 5E\text{-}05x^3 + 0.0076x^2 - 0.2488x + 198.82$ $R^2 = 0.9994$	$0.0004x^2 - 0.0351x + 207.32$ $R^2 = 0.9952$	$0.001x^2 - 0.5039x + 207.41$ $R^2 = 0.9999$
101-120	98.2	$8E\text{-}08x^4 - 4E\text{-}05x^3 + 0.0059x^2 - 0.1863x + 200.65$ $R^2 = 0.9994$	$0.0003x^2 - 0.0148x + 208.35$ $R^2 = 0.996$	$0.0008x^2 - 0.4495x + 209.33$ $R^2 = 0.9999$
121-140	97.5	$6E\text{-}08x^4 - 3E\text{-}05x^3 + 0.0047x^2 - 0.1415x + 203.44$ $R^2 = 0.9995$	$0.0002x^2 - 0.0014x + 210.45$ $R^2 = 0.9966$	$0.0007x^2 - 0.4048x + 211.98$ $R^2 = 0.9999$
141-160	92.3	$5E\text{-}08x^4 - 2E\text{-}05x^3 + 0.0038x^2 - 0.1096x + 210.03$ $R^2 = 0.9995$	$0.0002x^2 + 0.0072x + 216.45$ $R^2 = 0.997$	$0.0006x^2 - 0.3673x + 218.29$ $R^2 = 0.9999$
161-180	88.9	$4E\text{-}08x^4 - 2E\text{-}05x^3 + 0.0031x^2 - 0.0866x + 216.77$ $R^2 = 0.9996$	$0.0001x^2 + 0.0126x + 222.65$ $R^2 = 0.9973$	$0.0005x^2 - 0.3351x + 224.65$ $R^2 = 0.9999$
181-200	74.1	$3E\text{-}08x^4 - 2E\text{-}05x^3 + 0.0026x^2 - 0.07x + 218.72$ $R^2 = 0.9996$	$0.0001x^2 + 0.0158x + 224.13$ $R^2 = 0.9976$	$0.0005x^2 - 0.3072x + 226.2$ $R^2 = 0.9999$

Table 25. Relationship between carbon and poplar forest age. DOM carbon density is expressed as an equation where x refers to the age of the forest prior to the last fire (fire origin) or harvest (harvest origin), or the footprint age prior to reclamation (footprint origin).

Forest age (years)	Biotic carbon (tonne/ha)	Relationship for DOM carbon tonne/ha (and R^2)		
		Fire origin	Harvest origin	Footprint origin
0-20	9.4	$4E\text{-}07x^4 - 0.0002x^3 + 0.0241x^2 - 0.6612x + 187.95$ $R^2 = 0.9992$	$0.0025\ x^2-0.3232x+207.01$ $R^2=0.9976$	$0.0046x^2 - 1.2089x + 190.34$ $R^2 = 0.9972$
21-40	38.2	$3E\text{-}07x^4 - 0.0001x^3 + 0.0189x^2 - 0.5734x + 179.4$ $R^2 = 0.9992$	$0.0021\ x^2-0.2784x+191.03$ $R^2=0.9959$	$0.0023x^2 - 0.8107x + 181.31$ $R^2 = 0.9996$
41-60	60.8	$2E\text{-}07x^4 - 0.0001x^3 + 0.0147x^2 - 0.4527x + 176.97$ $R^2 = 0.9993$	$0.0015\ x^2-0.1885x+185.29$ $R^2=0.9959$	$0.0016x^2 - 0.6466x + 180.33$ $R^2 = 0.9999$
61-80	79.7	$2E\text{-}07x^4 - 8E\text{-}05x^3 + 0.0114x^2 - 0.349x + 178.82$ $R^2 = 0.9993$	$0.0011\ x^2-0.1182x+185.23$ $R^2=0.9966$	$0.0012x^2 - 0.5485x + 183.24$ $R^2 = 0.9999$

81-100	92.3	1E-07x⁴ - 6E-05x³ + 0.009x² - 0.2712x + 183.38 R^2 = 0.9994	0.0008 x²-0.069x+188.49 0.9972	0.001x² - 0.4778x + 188.44 R^2 = 1
101-120	98.1	9E-08x⁴ - 5E-05x³ + 0.0071x² - 0.2145x + 188.89 R^2 = 0.9994	0.0006 x²-0.0358x+193.07 R^2=0.9976	0.0008x² - 0.4226x + 194.09 R^2 = 1
121-140	92.4	7E-08x⁴ - 4E-05x³ + 0.0058x² - 0.1733x + 198.3 R^2 = 0.9995	0.0005 x²-0.0137x+201.78 R^2=0.9979	0.0007x² - 0.378x + 203.29 R^2 = 1
141-160	74.3	6E-08x⁴ - 3E-05x³ + 0.0048x² - 0.1431x + 211.84 R^2 = 0.9995	0.0004 x²+0.0007x+214.8 R^2=0.998	0.0006x² - 0.3411x + 216.81 R^2 = 1
161-180	51.5	5E-08x⁴ - 3E-05x³ + 0.004x² - 0.1205x + 223.97 R^2 = 0.9995	0.0003 x²+0.01x+226.52 R^2=0.9981	0.0005x² - 0.31x + 228.91 R^2 = 1
181-200	42.1	4E-08x⁴ - 2E-05x³ + 0.0035x² - 0.1035x + 219.44 R^2 = 0.9995	0.0003 x²+0.0158x+221.68 R^2=0.9982	0.0005x² - 0.2833x + 225.71 R^2 = 1

Table 26. Relationship between carbon and mixedwood forest age. DOM carbon density is expressed as an equation where x refers to the age of the forest prior to the last fire (fire origin) or harvest (harvest origin), or the footprint age prior to reclamation (footprint origin).

Forest age (years)	Biotic carbon (tonne/ha)	Relationship for DOM carbon tonne/ha (and R^2)		
		Fire origin	Harvest origin	Footprint origin
0-20	42.5	9E-08x⁴ - 8E-05x³ + 0.016x² - 0.6778x + 269.8 R^2 = 0.994	-4E-05x³ + 0.0187x² - 2.3156x + 358.62 R^2 = 0.9957	0.0055x² - 1.5031x + 257.99 R^2 = 0.9977
21-40	67.0	2E-07x⁴ - 0.0001x³ + 0.0171x² - 0.6424x +255.86 R^2 = 0.9989	-3E-05x³ + 0.0118x² - 1.4085x + 308.39 R^2 = 0.9948	0.0029x² - 1.0352x + 255.25 R^2 = 0.9997
41-60	80.7	2E-07x⁴ - 9E-05x³ + 0.0143x² - 0.5138x + 252.44 R^2 = 0.9994	-2E-05x³ + 0.0088x² - 1.0135x + 292.13 R^2 = 0.9949	0.002x² - 0.8395x + 256.57 R^2 = 0.9999
61-80	87.6	1E-07x⁴ - 7E-05x³ + 0.0111x² - 0.3934x + 253.66 R^2 = 0.9995	-2E-05x³ + 0.0071x² - 0.7886x + 286.33 R^2 = 0.9958	0.0016x² - 0.7195x + 259.86 R^2 = 1
81-100	98.6	9E-08x⁴ - 5E-05x³ + 0.0086x² - 0.3016x + 249.3 R^2 = 0.9995	-2E-05x³ + 0.0059x² - 0.6382x + 277.16 R^2 = 0.9967	0.0013x² - 0.6313x + 256.45 R^2 = 1
101-120	108.4	6E-08x⁴ - 4E-05x³ + 0.0067x² - 0.2349x + 252.15 R^2 = 0.9995	-1E-05x³ + 0.005x² - 0.5301x + 276.38 R^2 = 0.9974	0.0011x² - 0.5615x + 259.69 R^2 = 1
121-140	105.2	5E-08x⁴ - 3E-05x³ + 0.0053x² - 0.1869x + 259.42 R^2 = 0.9995	-1E-05x³ + 0.0043x² - 0.4495x + 280.8 R^2 = 0.9978	0.0009x² - 0.5044x + 267.02 R^2 = 1
141-160	91.2	4E-08x⁴ - 2E-05x³ + 0.0043x² - 0.1519x + 267.79 R^2 = 0.9995	-1E-05x³ + 0.0038x² - 0.388x + 286.85 R^2 = 0.9982	0.0008x² - 0.4566x + 275.25 R^2 = 1
161-180	78.0	3E-08x⁴ - 2E-05x³ + 0.0036x² - 0.1263x + 272.67 R^2 = 0.9995	-9E-06x³ + 0.0034x² - 0.3401x + 289.83 R^2 = 0.9984	0.0007x² - 0.4159x + 279.87 R^2 = 1
181-200	61.9	2E-08x⁴ - 2E-05x³ + 0.003x² - 0.107x + 267.47 R^2 = 0.9995	-8E-06x³ + 0.0031x² - 0.3019x + 283.03 R^2 = 0.9986	0.0006x² - 0.3808x + 274.35 R^2 = 1

Table 27. Relationship between years since disturbance (x) and the relative influence of pre-disturbance age on DOM carbon.

Forest type	Origin	Relationship between years since disturbance (x) and the relative influence of pre-disturbance age on DOM carbon
Spruce	Fire	1E-07x³ + 6E-05x² - 0.0107x + 0.9436 R^2 = 0.9983
	Harvest	-8E-08x³ + 4E-05x² - 0.0082x + 1.0238 R^2 = 0.9996
	Footprint	2E-09x⁴ - 1E-06x³ + 0.0002x² - 0.0159x + 0.9371 R^2 = 0.9953
Poplar	Fire	1E-09x⁴ - 7E-07x³ + 0.0001x² - 0.0155x + 0.9667 R^2 = 0.999
	Harvest	2E-09x⁴ - 8E-07x³ + 0.0002x² - 0.0152x + 0.9616 R^2 = 0.9986
	Footprint	2E-09x⁴ - 9E-07x³ + 0.0002x² - 0.0149x + 0.9481 R^2 = 0.997
Mixedwood	Fire	-3E-09x⁴ + 1E-06x³ - 0.0002x² + 0.0033x + 0.9781 R^2 = 0.9983
	Harvest	-1E-07x³ + 7E-05x² - 0.0118x + 1.0432 R^2 = 0.9986

	Footprint	$2E\text{-}09x^4 - 9E\text{-}07x^3 + 0.0002x^2 - 0.014x + 0.9496$ $R^2 = 0.9972$

Table 28. DOM carbon trajectory for footprints originating from forest. The relationship is based on CBM-CFS simulations of the conversion of 80-year old forest to oil and gas footprint.

Forest type prior to clearing	**Relationship between footprint age (x) and DOM carbon (tonnes/ha)**
Spruce	$5E\text{-}06x^4 - 0.0012x^3 + 0.1096x^2 - 5.1581x + 255.76$ $R^2 = 0.9989$
Poplar	$4E\text{-}06x^4 - 0.0009x^3 + 0.0865x^2 - 4.2202x + 230.76$ $R^2 = 0.9992$
Mixedwood	$4E\text{-}06x^4 - 0.0011x^3 + 0.1052x^2 - 5.1653x + 299.29$ $R^2 = 0.9991$