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Palaeolimnological assessment of lake acidification and environmental change in the Athabasca Oil Sands Region, Alberta

Chris J. CURTIS*, Roger FLOWER, Neil ROSE, James SHILLAND, Gavin L. SIMPSON, Simon TURNER, Handong YANG and Sergi PLA[1)]

Environmental Change Research Centre, University College London, Gower Street, London WC1E 6BT, United Kingdom
[1)]Center of Advanced Studies Blanes, CSIC C⁄ Acces Cala St Francesc, 14. Blanes, Girona 17300, Spain
*e-mail corresponding author: c.curtis@ucl.ac.uk

ABSTRACT

Exploitation of the Athabasca Oil Sands has expanded hugely over the last 40 years. Regional emissions of oxidised sulphur and nitrogen compounds increased rapidly over this period and similar emissions have been linked to lake acidification in other parts of North America and Europe. To determine whether lakes in the region have undergone acidification, 12 lakes within the Regional Municipality of Wood Buffalo and the Caribou Mountains were selected to cover chemical and spatial gradients and sediment cores were obtained for palaeolimnological analyses including radiometric dating, diatom analysis, isotopic analysis of bulk sediment ^{13}C *and* ^{15}N*, and spheroidal carbonaceous particles (SCPs). All lake sediment cores show evidence of industrial contamination based on SCPs, but there is no clear industrial signal in stable isotopes. Most lakes showed changes in diatom assemblages and sediment C:N ratios consistent with nutrient enrichment over various timescales, with potential drivers including climatic change, forest fires and anthropogenic nitrogen deposition. Only one of the 12 lakes investigated showed strong evidence of acidification with a decline in diatom-inferred pH from 6.3 to 5.6 since 1970 linked to increasing relative abundances of the acidophilous diatom species* Actinella punctata, Asterionella ralfsii *and* Fragilariforma polygonata*. Analysis of mercury (Hg) in the acidified lake showed increasing sediment fluxes over the last 20 years, a possible indication of industrial contamination. The acidified lake is the smallest of those studied with the shortest residence time, suggesting a limited capacity for neutralisation of acid inputs in catchment soils or by in-lake processes.*

Key words: diatoms, acid deposition, mercury, climate change, nitrogen deposition, ^{13}C*, Canada*

1. INTRODUCTION

Total reserves of oil within the Athabasca Oil Sands Region of northern Alberta are reported to be second in size only to those in Saudi Arabia. Low level extraction activities commenced in the region in the 1960s, but major global increases in the price of oil have led to a massive expansion of extraction activities in recent years. Production levels are predicted to increase by as much as three times from 2006 levels by 2015 (Pelley 2006). The subarctic boreal forest in this region contains large numbers of lakes which may be vulnerable to the combined effects of climate change and acid deposition produced by the emission of sulphur and nitrogen compounds from fossil fuel combustion (Schindler 1998).

Recent research programmes funded by multi-stakeholder groups in the region (e.g., the Cumulative Environmental Management Association, CEMA and the Wood Buffalo Environmental Association, WBEA) have investigated both the present and potential impacts of industrial activities associated with oil extraction on natural ecosystems and human health. Of particular concern are the impacts of industrial activities on traditional aboriginal uses of the land, including hunting and fishing. Lake acidification is a well-known impact of acid deposition in regions of slow weathering bedrock and has occurred in eastern Canada and the USA (e.g., Schindler 1988; Charles 1991; Jeffries 1997; Stoddard *et al*. 1999; Jeffries *et al*. 2003; Whitfield *et al*. 2007) and many parts of Europe (e.g., Kamari *et al*. 1991; Henriksen *et al*. 1992; 1998; Curtis *et al*. 2000, 2005). Surveys of lake water chemistry in northern Alberta carried out by another multi-stakeholder group, the Regional Aquatics Monitoring Programme (RAMP) have identified acid sensitive lakes in many parts of the region (e.g., RAMP 2008). Hence the potential for acidification of surface waters by sulphur and nitrogen emissions from industrial activities in the Alberta Oil Sands Region requires urgent assessment.

The study of subfossil diatom remains in lake sediment cores is a well established technique for reconstructing changes in lakewater acidity through time and demonstrating acidification caused by acid deposition (e.g., Flower & Battarbee 1983; Battarbee *et al*. 1985; 1990; Smol *et al*. 1986). A previous palaeolimnological study of eight lakes in the Oil Sands Region found no evidence of acidification, but was focussed on larger lakes of relatively low acid-sensitivity (Hazewinkel *et al*. 2008). This study therefore concluded that the lack of evidence for acidification in these lakes did not indicate there was no risk of lake acidification in the region and that further, more focussed studies were needed.

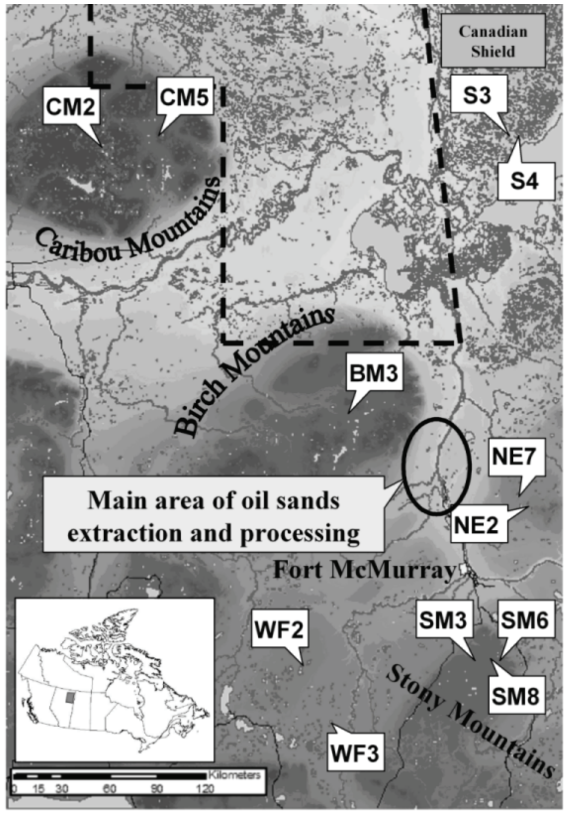

Fig. 1. Distribution of study sites for lake sediment core analysis. Dotted line marks approximate location of Wood Buffalo National Park.

The aim of the present study was to expand the palaeolimnological approach to a further 12 lakes, to include smaller and more acid-sensitive sites across spatial and chemical gradients. In addition to diatom analysis and radiometric dating of sediment cores, several additional analyses for indicators of industrial contamination were included: spheroidal carbonaceous particles (SCPs) are unambiguous indicators of deposition arising from fossil fuel combustion; stable isotopes of ^{13}C and ^{15}N may provide evidence of disturbance to lake biogeochemistry *via*, amongst others, anthropogenic N deposition and, with associated C:N ratios, provide information on changes to sources of organic matter in lake sediments; and mercury analysis can provide evidence of possible industrial contamination.

2. METHODS

2.1. Site selection and lake coring

The study region incorporates the Regional Municipality of Wood Buffalo (RMWB; area 68,454 km^2, 2006 population *ca* 90,000) and the Caribou Mountains west of Wood Buffalo National Park (approximately 11,000 km^2; Fig. 1). Selection of lakes for coring was based partly on a previous study of surface sediments from 45 lakes in the region and core bottom samples from a subset of these lakes (Pla *et al*. 2006). Diatom analysis of the 45 surface sediment samples obtained during 2003 and 2004 was used in conjunction with contemporary water chemistry from the RAMP Acid Sensitive Lakes programme (RAMP 2007) to derive the previous diatom-pH transfer function using bootstrapped weighted averaging partial-least-squares regression (WA-PLS: ter Braak *et al*. 1993; $RMSEP_{boot}$ = 0.38, maximum bias = 0.65; see Hazewinkel *et al*. 2008 for full description of sites and methods). Sediment core bottom samples, undated but assumed to be pre-industrial, were analysed for diatoms for comparison with surface sediment samples and both the magnitude of change in diatom assemblages (measured as chord distance; Overpeck *et al*. 1985; Gavin *et al*. 2003) and diatom-inferred pH from the transfer function were calculated. The sediment core top data from this previous study were used in combination with the new cores collected for the present study to derive a new diatom-pH inference model.

Final site selection for new coring was to provide regional coverage and a gradient of acid sensitivity from low (pH >6.5) to sensitive (pH 6.0–6.5) and acidic (pH <6.0) lakes (Fig. 1, Tab. 1). Based on the previous work comparing core surface and bottom samples (Pla *et al*. 2006), all selected lakes with existing data showed major changes in diatom assemblages measured as chord distance, but a variety of changes in diatom-inferred pH (DI-pH) from no change to a large decline in DI-pH from core bottoms to surface samples. Some of the lakes selected for coring were not included in the previous study so no measure of diatom change or DI-pH were available. Lakes SM8 and NE7 were priori-

Tab. 1. Twelve lakes selected for palaeolimnological study. * Data from Bennett *et al*. (2008).

CEMA Code	Coring location		Lake area*	Max depth*	Lake vol.*	Catchment area*	C:L ratio	Residence time*	Core ID	Coring date	Coring depth	Core length	Acid sensitivity	Sediment Hg concentration
	Latitude	Longitude												
	(decimal degrees)		(ha)	(m)	(10^6 m^3)	(km^2)		(years)			(m)	(cm)		(ng g^{-1})
Birch Mountains														
BM3	57.65232	112.61289	96.6	4.6	1.33	28.6	29.6	0.46	ALB02	21-Aug-06	3.10	0–25.5	low	129.7
Caribou Mountains														
CM2	59.11909	115.12837	955	6.0	27.32	37.9	4.0	2.06	ALB15	25-Aug-06	5.40	0–35.0	low	111.1
CM5	59.23804	114.52351	55.2	1.5	0.87	2.6	4.7	1.49	ALB16	25-Aug-06	1.30	0–18.0	sensitive	107.1
North-east of Fort McMurray														
NE2	57.09281	110.75042	33.7	1.8	0.43	17.0	50.5	0.33	ALB09	23-Aug-06	1.65	0–24.5	sensitive	121.6
NE7	57.14667	110.86483	11.2	2.0	0.11	4.1	36.4	0.19	ALB21	30-Aug-06	1.50	0–25.0	acidic	137.8
Shield lakes north of Lake Athabasca														
S3	59.19059	110.67251	144.8	10.6	4.84	29.7	20.5	1.31	ALB18	26-Aug-06	10.50	0–33.5	low	66.8
S4	59.16801	110.56855	141.6	9.5	5.64	123.1	86.9	2.41	ALB17	26-Aug-06	9.50	0–32.0	low	123.7
Stony Mountains														
SM3	56.20155	111.36388	186.1	3.1	2.69	7.7	4.1	1.55	ALB05	22-Aug-06	3.10	0–26.0	sensitive	91.7
SM6	56.22227	111.17004	69.9	1.6	0.62	3.4	4.9	0.81	ALB04	22-Aug-06	1.60	0–19.0	acidic	93.5
SM8	56.21567	111.20536	191.3	2.5	1.69	9.7	5.1	0.85	ALB03	22-Aug-06	1.40	0–18.5	acidic	93.6
West of Fort McMurray														
WF2	56.24551	113.14144	75.5	1.8	0.71	23.4	30.9	1.45	ALB12	24-Aug-06	1.60	0–38.0	low	89.7
WF3	55.90871	112.86468	216.4	2.0	2.09	38.1	17.6	1.02	ALB11	24-Aug-06	1.20	0–25.0	acidic	102.7

tised since these sites were to be intensively monitored for use in application of the dynamic acidification model MAGIC (Whitfield *et al*. 2010, this issue). Details of the 12 finally selected lakes are given in table 1 and their locations in figure 1.

Sediment coring was carried out by UCL staff joining the RAMP regional lakes survey during August 2006. Duplicate cores were obtained using a HTH gravity corer (Renberg & Hansson 2008) from the deepest part of each lake where possible, directly from a float plane or (for very small lakes) float helicopter. The primary core, judged by visual assessment as the least disturbed and/or longest core, was used for palaeolimnological analysis while the second core was extruded and retained to provide archived back-up material. Intact cores were transported back to the field station where they were extruded at 0.5 cm intervals and samples kept refrigerated at 4 °C prior to analysis. Water chemistry samples collected at the same time for the RAMP survey provided the latest data points for the RAMP 2007 Annual Report, summarised for cored lakes in table 2. See RAMP (2007) for water chemistry analytical methods.

2.2. Palaeolimnological analyses

2.2.1. Sediment sub-sampling

The suite of analyses performed on each core included the following: (1) lithostratigraphy (dry weight and loss-on-ignition (LOI)), (2) radiometric dating (^{210}Pb, ^{137}Cs), (3) diatom analysis, (4) spheroidal carbonaceous particle (SCP) analysis and (5) sediment isotopic analysis ($\delta^{15}N$ and $\delta^{13}C$). In addition, mercury analysis was undertaken on the core from NE7.

Since several of these analyses are destructive, the following sequential strategy was employed to ensure sufficient sediment material for all analyses, based on the 0.5 cm extrusion intervals: (1) wet density was sampled every 3 cm (used in ^{210}Pb method) starting at the surface sample (0–0.5 cm, 3.0–3.5 cm, etc.) and all intervals were subsequently dried, (2) dry weight and LOI were determined on subsamples from the surface sample and then every second interval starting at 0.5–1.0 cm, (3) intervals for ^{210}Pb dating were tailored to each core, based on an initial skeleton analysis and then in-filled to cover the record in more detail, (4) diatom analysis; depending on core length, 18–20 levels were analysed sequentially, usually at 1 cm intervals, (5) levels for SCP analysis were selected to cover the last 150 years based on the chronology determined by the ^{210}Pb results and (6) sediment isotopic analysis of subsample ($\delta^{15}N$ and $\delta^{13}C$) on the 0.25 and 0.75 cm samples and thence every 1 cm. Hg analyses were performed on all surface sediment samples and the site with the greatest concentration was selected for down-core Hg analysis.

2.2.2. Dry weight and loss-on-ignition (LOI) analysis

Sediment dry weight and LOI determinations were made gravimetrically following heating of sediment sub-samples to 105 °C and 550 °C respectively. These analyses are routinely carried out during stratigraphic studies to provide a check for major changes in organic matter content of sediment cores which might indicate changes in sedimentation regimes or sediment in-wash events. Wet density measurements were undertaken on every sixth sample by evenly filling wet sediment into a 2 cm^3 measurement vial and weighing on an electronic analytical balance to four decimal places.

Tab. 2. Selected water chemistry for the 12 cored lakes (source: RAMP 2007).

CEMA Code		Cond ($\mu S\ cm^{-1}$)	pH	Ca ($\mu eq\ L^{-1}$)	Mg	Na	K	Cl	SO_4	NH_4	NO_3	Alk	ANC	TDN ($\mu g\ L^{-1}$)	TDP	DOC ($mg\ L^{-1}$)
BM3	Min	46.2	6.87	280.4	155.5	82.7	DL	2.1	107.9	1.1	DL	253.8	409.7	693.3	31.1	17.3
BM3	Mean	55.5	7.05	324.6	168.5	110.5	12.3	3.5	154.4	2.4	1.3	309.0	459.2	903.1	46.6	20.9
BM3	Max	60.9	7.30	377.2	185.1	122.7	16.9	5.2	200.7	4.0	0.6	372.0	499.3	1590.5	59.9	23.3
CM2	Min	20.1	6.80	195.1	86.8	18.2	DL	3.2	30.9	0.8	DL	194.2	266.8	417.1	6.9	12.0
CM2	Mean	28.5	6.87	212.3	90.6	23.0	6.6	4.2	40.3	3.4	1.1	211.3	290.3	612.5	9.9	13.5
CM2	Max	32.4	6.99	253.5	101.2	29.1	10.7	5.3	52.8	2.0	0.7	242.0	337.8	1050.1	14.2	15.9
CM5	Min	15.8	6.04	150.7	55.1	14.4	DL	2.7	18.2	1.0	DL	83.6	200.1	565.8	14.3	17.8
CM5	Mean	20.2	6.27	165.7	61.1	31.6	3.9	4.0	27.5	1.7	0.8	112.0	231.6	978.1	19.0	21.6
CM5	Max	22.7	6.48	188.6	70.0	63.8	6.1	6.2	30.6	5.1	0.4	130.0	296.4	2425.3	23.5	28.2
NE2	Min	23.6	6.05	183.6	89.7	20.9	DL	1.4	8.3	0.8	DL	131.9	285.3	455.1	6.4	25.7
NE2	Mean	26.8	6.26	225.8	106.4	28.3	4.1	2.8	12.2	1.2	0.8	157.0	350.1	753.1	9.7	30.4
NE2	Max	30.6	6.70	287.9	120.9	33.9	6.9	3.7	15.6	0.6	0.6	201.8	430.4	1660.0	12.1	33.7
NE7	Min	19.3	4.90	114.8	65.0	16.3	DL	2.1	6.2	0.9	DL	52.6	188.7	527.8	6.9	27.0
NE7	Mean	22.4	5.13	167.8	80.0	21.9	1.6	4.8	9.2	2.3	1.5	62.5	258.1	636.9	7.7	31.6
NE7	Max	24.0	5.37	203.6	93.0	26.5	3.8	9.5	15.9	6.0	0.6	78.4	306.9	724.0	8.3	34.2
S3	Min	39.3	7.03	226.0	128.3	62.5	9.2	30.0	7.4	1.2	DL	301.2	389.9	398.9	2.9	14.2
S3	Mean	42.1	7.08	243.2	136.0	67.4	13.3	33.9	14.3	1.5	0.5	306.9	412.7	525.0	3.4	19.8
S3	Max	49.8	7.14	302.9	153.0	71.3	18.7	37.1	25.1	0.6	0.5	311.6	483.9	636.1	4.1	33.4
S4	Min	50.8	7.20	286.4	178.5	60.4	15.1	29.6	20.4	0.8	DL	410.6	491.2	388.3	1.2	12.1
S4	Mean	53.6	7.23	315.9	193.6	66.1	17.7	31.7	31.8	0.7	0.2	435.9	530.3	448.1	3.8	15.2
S4	Max	55.1	7.29	407.2	218.8	73.9	27.9	39.7	49.2	0.5	0.2	451.8	639.3	533.0	5.0	24.2
SM3	Min	11.7	6.37	86.8	41.1	22.9	2.6	3.6	7.9	0.8	DL	90.0	142.7	440.0	5.1	11.9
SM3	Mean	15.5	6.42	94.6	47.8	26.5	8.6	6.1	19.1	0.5	0.1	98.3	152.8	467.0	5.5	12.4
SM3	Max	17.2	6.47	109.3	53.5	29.2	10.5	9.5	27.0	0.5	0.2	103.2	166.2	515.0	6.2	13.0
SM6	Min	11.6	5.09	54.9	29.0	15.1	DL	3.3	19.7	1.1	0.7	32.6	76.5	611.0	16.7	12.0
SM6	Mean	13.6	5.30	64.5	33.8	22.9	10.0	4.2	24.8	3.0	2.8	41.1	102.2	722.5	25.6	15.4
SM6	Max	15.6	5.45	74.4	41.1	33.5	13.3	5.3	34.7	5.4	4.5	49.6	123.1	828.0	44.8	16.7
SM8	Min	12.1	4.82	47.4	22.3	14.9	DL	3.2	25.9	1.5	DL	21.2	56.9	593.0	20.2	14.3
SM8	Mean	13.1	5.01	56.6	25.7	25.1	8.8	5.6	30.4	2.0	0.2	30.2	82.0	772.1	28.3	17.0
SM8	Max	14.1	5.18	65.9	28.8	39.1	13.8	7.3	39.8	0.7	0.5	37.2	100.6	1120.0	33.2	20.1
WF2	Min	27.4	6.53	210.6	74.9	29.6	7.2	7.3	19.1	1.0	9.6	158.0	287.1	953.5	24.0	19.0
WF2	Mean	33.5	6.67	248.7	81.5	35.7	17.7	10.4	35.3	2.6	22.5	192.2	318.0	1301.3	37.8	20.4
WF2	Max	38.2	6.79	317.9	93.8	54.7	23.3	13.1	42.9	4.7	6.0	216.2	432.3	1924.1	70.3	21.5
WF3	Min	20.2	4.76	92.8	57.4	35.7	1.8	3.4	18.5	0.9	0.1	22.6	166.5	647.7	13.5	30.0
WF3	Mean	24.3	5.11	146.4	63.0	46.7	11.0	12.3	33.9	5.6	1.0	60.3	225.5	944.3	25.8	33.3
WF3	Max	28.8	5.67	166.2	69.9	63.9	16.9	41.9	56.7	0.5	0.4	95.8	218.4	1464.6	50.2	35.6

2.2.3. Radiometric dating

Sediment samples were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Bloomsbury Environmental Isotope Facility (BEIF) at University College London, using an ORTEC HPGe GWL series well-type coaxial low background intrinsic germanium detector. ^{210}Pb was determined *via* its gamma emissions at 46.5 keV, and ^{226}Ra by the 295 keV and 352 keV gamma rays emitted by its daughter isotope ^{214}Pb following three weeks storage in sealed containers to allow radioactive equilibration. Caesium-137 and ^{241}Am were measured by their emissions at 662 keV and 59.5 keV. The absolute efficiencies of the detector were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self absorption of low energy gamma rays within the sample. Core chronologies were calculated using the constant rate of supply (CRS) model (Appleby 2001).

2.2.4. Diatom analysis

Diatom slides were prepared according to Battarbee *et al.* (2001) and identifications followed the published literature (Hohn & Hellerman 1963; Patrick & Reimer 1966–1977; Krammer & Lange-Bertalot 1986, 1988, 1991; Lange-Bertalot & Krammer 1989; Camburn & Charles 2000; Flower 2005; Siver *et al.* 2005). Diatom analysis was undertaken using a Leitz Labrolux light microscope equipped with a phase contrast oil immersion 1.3 NA × 100 objective. Approximately 300 valves were counted in each level (except for those sediment sections where diatom preservation was poor).

A revised Weighted Averaging – Partial Least Squares regression (WA-PLS) (ter Braak *et al.* 1993) diatom-pH transfer function model based on the previous 45 sediment core top samples (Pla & Curtis 2006; Hazewinkel *et al.* 2008) plus the current study sites was used to reconstruct pH histories for lake sediment cores, following taxonomic harmonization of diatom counts and combination of the two core top datasets. All diatom taxa and all surface sediments were used to build the new model and all counts from the sediment record were used for pH reconstruction. No taxa were omitted to avoid poor correlation between sediment core taxa and training set taxa, in order to produce the most correct reconstruction despite the potential loss of predictive power from the model. Model performance was

Tab. 3. Diatom-pH transfer function (WA-PLS) models using 1–5 components (C1–C5).

Name	RMSE	R^2	Av. Bias	Max. Bias	Boot. R^2	Boot. Av. Bias	Boot. Max. Bias	RMSE s1	RMSE s2	RMSEP
C1	0.3055	0.8528	0.0000	0.7323	0.6876	–0.0315	0.8704	0.1298	0.4588	0.4768
C2	0.1672	0.9559	0.0000	0.2617	0.6902	–0.0588	0.8433	0.1522	0.4490	0.4741
C3	0.1073	0.9818	0.0000	0.1736	0.6921	–0.0568	0.8360	0.1729	0.4471	0.4794
C4	0.0718	0.9919	0.0000	0.1121	0.6867	–0.0589	0.8749	0.1822	0.4511	0.4865
C5	0.0480	0.9964	0.0000	0.0399	0.6815	–0.0608	0.9092	0.1925	0.4547	0.4938

assessed using bootstrap cross-validation (Birks *et al*. 1990).

WA-PLS models with between 1 and 5 components were produced and evaluated in terms of $RMSEP_{boot}$ (Tab. 3). The simplest one component model (C1: $RMSEP_{boot}$ = 0.4768, R^2 = 0.6876) performed almost as well as the two component model (C2: $RMSEP_{boot}$ = 0.4741, R^2 = 0.6902) with a deterioration in $RMSEP_{boot}$ thereafter as further components were added (Tab. 3). Hence the one-component model (WA-PLS C1) was used here to determine diatom-inferred pH for reconstruction.

2.2.5. Spheroidal carbonaceous particles

Spheroidal carbonaceous particle (SCP) analyses were undertaken following the method described in Rose (1994). SCPs were counted using a light microscope at ×400 magnification and the sediment concentration calculated in units of 'number of particles per gram dry mass of sediment' (g DM^{-1}). The criteria for SCP identification under the light microscope followed Rose (2008). Analytical blanks and SCP reference material (Rose 2008) were included in each batch of sample digestions. Reference concentrations agreed with the expected values while no SCPs were observed in the blanks. The detection limit for the technique is *ca* 100 gDM^{-1} and concentrations have an accuracy of *ca* ± 45 gDM^{-1}.

2.2.6. Stable isotope analysis

Bulk organic matter sub-samples from sediment cores from each lake were air dried at 40 °C or below. These sub-samples were then milled to a fine powder using a Retsch mixer mill. Approximately 0.001 g of milled sediment was transferred to pre-weighed tin capsules, which were then sealed. The amount of dried sediment in each capsule was recorded.

The samples were analysed for total N and C, $^{14}N/^{15}N$ and $^{12}C/^{13}C$ at the UC Davis Stable Isotope Facility, California, USA on Hydra 20-20 or Anca-GSL isotope ratio mass spectrometers. The concentration of N and C in the samples is expressed as grams N or C per gram dry weight of sediment. The isotopic ratio of $^{14}N/^{15}N$ and $^{12}C/^{13}C$ is expressed using the delta (δ) notation in parts per thousand (or *per mille*, ‰), where $\delta^{15}N$ (‰) and $\delta^{13}C$ (‰) = $[(R_{sample} / R_{standard}] - 1] \times 1000$, where R is the $^{14}N/^{15}N$ or $^{12}C/^{13}C$ ratio in the measured sample or the appropriate standard. The standard for nitrogen is the $\delta^{15}N$ of atmospheric nitrogen (commonly referred to as AIR), and for $\delta^{13}C$ the standard is Vienna Pee Dee Belemnite (VPDB). The C/N ratio was calculated from the mass of N and C and converted to atomic ratios by multiplying the mass ratios by 1.167 (the ratio of the atomic weights of N and C).

2.2.7. Mercury analysis

Mercury analyses were performed on surface sediment subsamples from the cored lakes and then down the core profile for the lake with the greatest surface sediment concentration using freeze dried, milled samples on a Milestone DMA-80 Direct Mercury analyser. Concentration data were converted to fluxes using sediment accumulation rates calculated from the ^{210}Pb chronology.

3. RESULTS

3.1. Lithostratigraphic analysis

The cores show a wide range in organic matter content as illustrated by LOI values ranging from <20% in S3 to >80% in WF2. The presence of dramatic short-term fluctuations in dry weight or LOI can indicate that stratigraphic integrity has been compromised e.g., through discontinuities in the record. While there are few such indications in the present core records, there are small shifts in LOI in the bottom of core ALB04 (lake SM6) and at 5 cm depth in both ALB02 (lake BM3) and ALB05 (lake SM3) (data not shown, see Curtis *et al*. 2009).

3.2. Sediment core chronologies

Dating of sediment cores using ^{210}Pb and ^{137}Cs reveals a large range of sediment accumulation rates, but all 12 cores encompass at least 100 years of accumulated sediment. Most cores showed straightforward dating profiles, although three showed possible evidence of missing surface sediments (lakes SM8, WF3 and S3) introducing uncertainty into the interpretation of very recent changes. Age-depth profiles and sedimentation rates for individual cores are presented in Curtis *et al*. (2009).

3.3. Diatom analysis

The sedimentary diatom assemblages examined in the 12 cores displayed a wide diversity of species, both planktonic and benthic, that are closely linked to

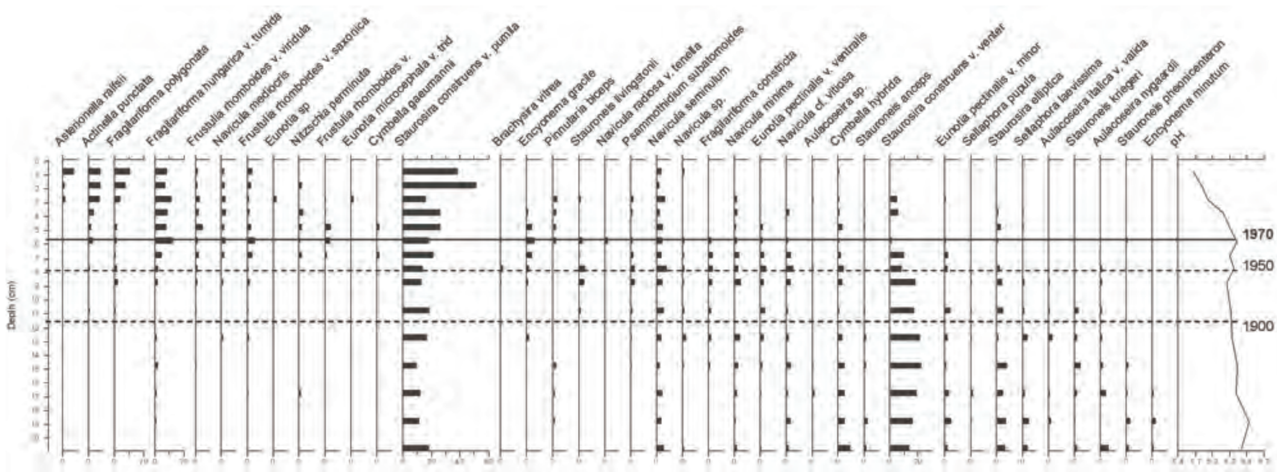

Fig. 2. Diatom inferred pH change in lake NE7 (core ALB21).

Tab. 4. Summary of the principal overall changes indicated by trends in diatom frequency abundances in 12 lake sediment cores.

Lake / Core	Acidified	Nutrient enriched	High diatom plankton	Species diversity
BM3 / ALB02	No – slight pH increase	yes	yes	high
CM2 / ALB15	No – pH increasing since pre-1900	yes	yes	moderate
CM5 / ALB16	No – pH increasing since 1980s	yes	no	poor
NE2 / ALB09	No – no pH change	no	no	moderate
NE7 / ALB21	Yes – pH decline	no	no	moderate
S3 / ALB18	No – no pH change	yes	no	moderate
S4 / ALB17	No – no pH change	yes	yes	high
SM3 / ALB05	No – slight pH decline	no	no	low
SM6 / ALB04	No – no pH change	yes	no	moderate
SM8 / ALB03	No – pH increasing since pre-1900	slightly	no	low
WF2 / ALB12	No – pH increasing since c.1990	yes	no	moderate
WF3 / ALB11	No – pH increasing since pre-1900	yes	yes	moderate

regional water quality variations as well as to specific local site factors. Many of the species are cosmopolitan but North American species (e.g., *Stephanodiscus niagarae* Ehr., *Cyclotella michiganiana* Skv.) often contribute significantly to the diatom phytoplankton component. Endemic benthic taxa are less significant but occurrences of rare taxa such as *Carpartogramma crucicula* (Grun. ex Cl.) Ross, *Pinnularia cuneicephala* Smith, *P. latevittata* v. *domingensis* Cleve and *Stauronies stodderi* Lewis are noteworthy. Some small naviculoids in several cores, present in relatively low abundances, were taxonomically problematic.

Diatom analysis of the 12 cores indicates that the lakes can be placed broadly into three categories that indicate lake acidification, nutrient enrichment or an absence of significant change. The diatom stratigraphies of three cores are presented to indicate these categories. Only one of the sites (lake NE7, core ALB21) indicates marked recent acidification (Fig. 2). Diatom assemblages in this core were moderately diverse (123 taxa being identified) and showed marked species changes. Although circum-neutral species such as tychoplanktonic *Staurosira construens* v. *pumila* dominated the diatom assemblages, acid water indicator diatoms and especially *Actinella punctata* appear towards the core top (Fig. 2). *Actinella punctata* indicates strongly acid water and has pH optima of 5.1 in North American (Dixit *et al.* 1993) and 5.2 in European (Birks *et al.* 1990) data sets. It appears in the core at between 6 and 7 cm depth (*ca* 1970) and increases in abundance particularly in the upper 3 cm or from *ca* 1990. Other acid indicating species such as the planktonic *Asterionella ralfsii* and tychoplanktonic *Fragilariforma polygonata* also showed sharp increases in the upper 3 cm of sediment. *Frustulia rhomboides* v. *saxonica* and several circum-neutral *Cymbella* and *Navicula* taxa showed small abundance peaks around 5.5–7.5 cm depth (*ca* 1950–70). Other circum-neutral and tychoplanktonic taxa such as *Staurosira elliptica* and several *Aulacoseira* spp. showed abundance declines towards the core top. No species typical of nutrient enrichment were observed. Overall, this core provides strong evidence that the lake has been recently acidified with a marked DI-pH decline from about pH 6.3 to pH 5.6 since 1970 (Fig. 2). Although two other cores (ALB04 from lake SM6 and ALB09 from lake NE2, Tab. 4) indicated slight acidification, only NE7 displayed a convincing declining pH trend.

Several sites showed increases in diatom-inferred pH (alkalinisation) and many of the sites appear to have

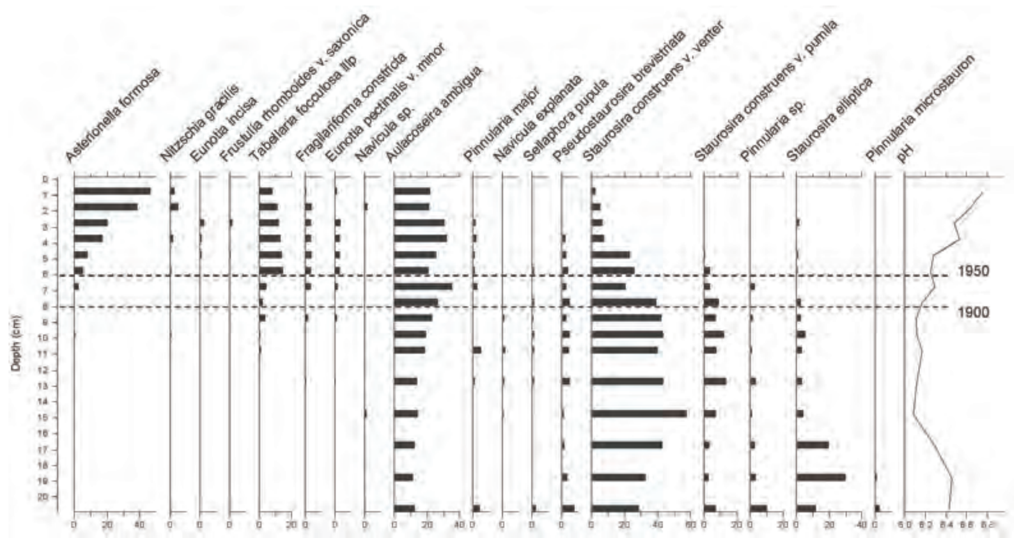

Fig. 3. Increasing abundance of the planktonic diatom *Asterionella formosa* and diatom-inferred pH in lake WF3 (core ALB11).

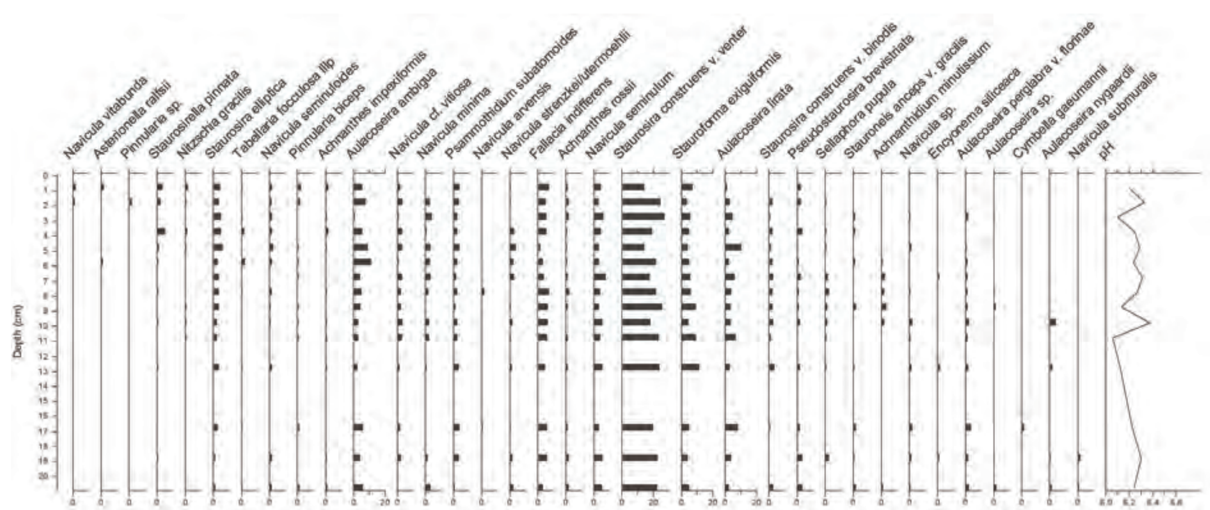

Fig. 4. Stable diatom communities in lake NE2 (core ALB09).

experienced nutrient enrichment in the recent past (Tab. 4). This is typically demonstrated by the increasing abundance of planktonic diatoms commonly associated with more nutrient rich conditions, for example the major increase of *Asterionella formosa* in lake WF3 (core ALB11; Fig. 3). This taxon was unrecorded below 12 cm depth and showed a major abundance increase from above 7 cm depth (*ca* 1936) to reach almost 50% of the total diatom assemblage in surface sediment. Another planktonic diatom, *Aulacoseira ambigua*, also indicative of nutrient enrichment, also showed increasing frequency abundances, from the core base to the most recent sediment. Less common but also indicating increased nutrients, *Nitzschia gracilis* increased in the recent sediment. Commensurate with the increasing abundances of these taxa indicating higher nutrient status, several fragilarioids declined in the core. These taxa are primarily benthic but are easily resuspended into the water column and *Staurosira elliptica* and *St. construens* v. *venter* both show strong declines and only *Fragilariforma constricta* shows a small increase. Similarly, some of the more uncommon but larger benthic *Pinnularia* species have also declined in abundance. Possibly, these changes could reflect diminished underwater light availability as a result of the development of the planktonic diatoms and doubtless other phytoplankton; alternatively, nutrient or light optima of the benthic species may have changed. Overall, the diatom stratigraphy of this core shows a large increase in planktonic diatom species that indicates strong nutrient enrichment of the lake. There is a corresponding increase in diatom-inferred pH from pre-1900 to the present day, although higher pH values were also indicated at the core base.

Diatom analysis in two cores cores (ALB09 from lake NE2 and ALB04 from lake SM6) showed no marked trend changes in diatom abundances indicating an absence of significant eutrophication or acidification. The diatom frequency diagram for lake NE2 (Fig. 4)

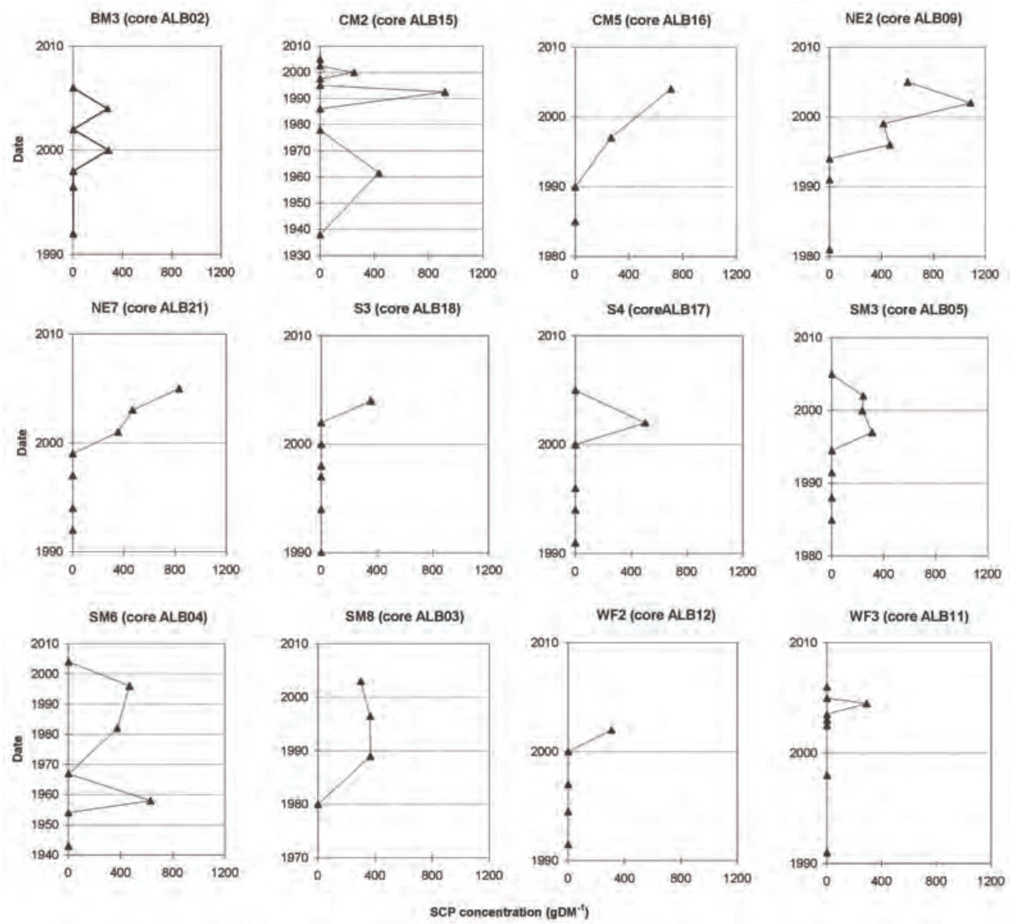

Fig. 5. SCP concentration profiles for the 12 cores plotted on radiometric date axes.

showed relatively small changes in species composition. The semi-benthic fragilarioid species *Staurosira construens* v. *venter* was common throughout the sediment core with abundances fluctuating around 20% without any clear trend change. Several diatoms showed a small trend towards higher abundances from the core base to around 7–5 cm sediment depth (*ca* 1960–1976) before declining. One of these species *Aulacoseira ambigua* is an indicator of higher nutrient conditions. Only two low abundance species increased above 6 cm depth (1969), *Asterionella ralfsii* and *Staurosira elliptica*. The former species is planktonic in habit and could indicate a small acidity change, but the minor increase in *A. ambigua* could indicate slight nutrient enrichment around 5 cm depth in the core (*ca* 1976) with a subsequent decline suggesting that this change was not sustained. Overall, the diatom stratigraphy of this core indicates fairly stable conditions with hints of acidity and nutrient changes which are not detectable in the diatom-inferred pH, which shows no convincing trend.

3.4. SCP analysis

Spheroidal carbonaceous particles (SCPs) provide an unambiguous indicator of contamination from high-temperature fossil fuel combustion (coal and fuel oil, but not gas) because they are not produced from wood, biomass or charcoal combustion (e.g., forest fires) and hence have no natural sources (Rose 2001). SCPs were found at low but detectable concentrations in all cores. The highest recorded concentration exceeded 1000 gDM^{-1} only in lake NE2 (core ALB09; see Fig. 5). No SCPs were detected below 5 cm in any core suggesting any contamination is recent. This is confirmed by the radiometric dating which shows that the earliest presence of SCP contamination was found in lake SM6 (core ALB04) in the late 1950s and in lake CM2 (core ALB15) in the 1960s (Fig. 5). Temporal profiles are highly irregular and, given the low concentrations, the SCP temporal records are likely to be linked to detection limits of the analytical technique. As a consequence, the first presence of SCPs in the cores is not synchronous across the region and the profiles show no consistent temporal trends.

Full SCP inventories were calculated for each core. These provide a measure of the full record of contamination at each lake. These have also been normalised to the ^{210}Pb inventories for each core in order to allow for both sediment focussing effects in each lake and enhanced catchment inputs from, for example, bare rock areas. Both SCP inventories and SCP/^{210}Pb inventory

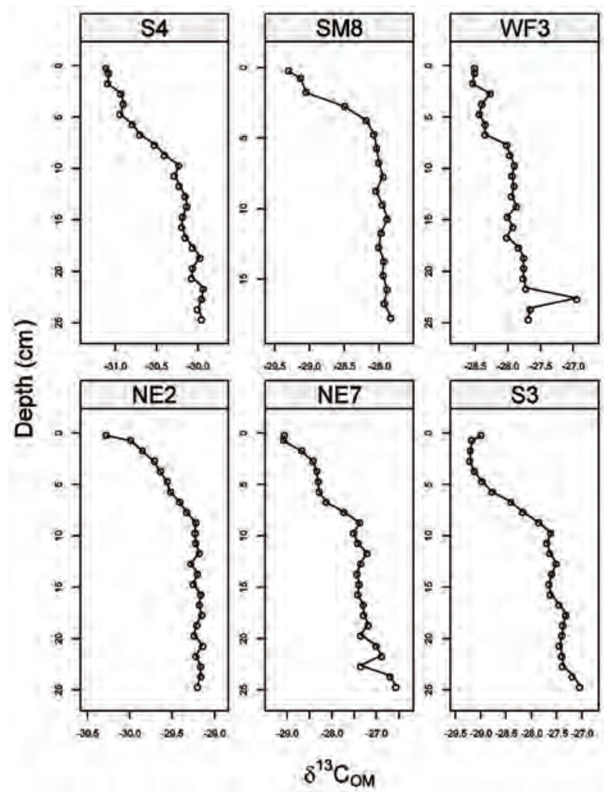

Fig. 6. δ^{13}C in bulk sediment organic matter of selected lakes.

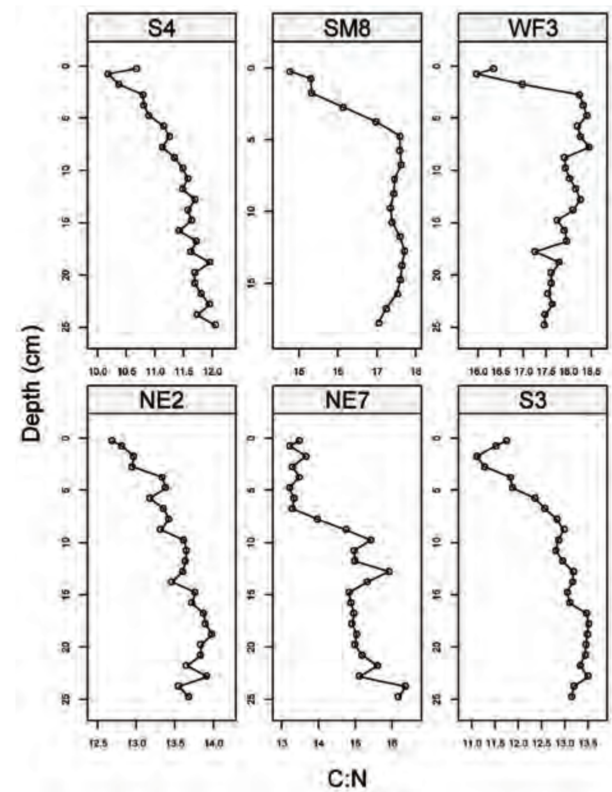

Fig. 7. C:N ratio in bulk sediment organic matter of selected lakes.

ratios confirm the low contamination status of all the lakes. Analysis of the full dataset shows no relationship of any SCP parameter (surface and peak concentrations; surface fluxes; inventories and inventory ratios) with distance from the centre of the Oil Sands processing activities. This indicates that these activities are not a major source of these particulate contaminants. The SCP data also show no agreement with the Hg surface sediment concentrations (see below).

3.5. Stable isotope analysis

The δ^{13}C and C/N ratio profiles demonstrate the clearest signs of alterations in lake biogeochemistry, including sources of organic matter and changes in productivity. Figure 6 shows the measured δ^{13}C profiles for selected lakes.

The δ^{13}C values are all indicative of contributions from lacustrine organic matter (algae) or C3 land plants, with values of –27‰ to –31‰ observed across the set of study lakes. The observed changes in δ^{13}C values are all towards isotopically lighter organic matter in more recent sediments, but changes are small, on the order of <1‰–2‰. The changes in lakes S3, S4, NE2, NE7 and SM8 document the most significant shifts in δ^{13}C values following relatively stable periods of isotopically heavier material (Fig. 6). In lakes S3, S4 and NE7 the observed switch to isotopically lighter organic matter occurred around 1930, while the changes in NE2 and SM8 occur somewhat later.

There are few strong, consistent shifts in the δ^{15}N values, with most lakes having low (~2‰ to 3‰) but highly variable δ^{15}N values. There are clear increases of ~1‰ in δ^{15}N values in lakes CM5 and NE7 and to a lesser extent in WF2 and SM8. In WF2, CM5 and NE7, the trends occur throughout the retrieved sediment cores and precede the industrialisation in Western countries and the later Oil Sands activities, whereas the increase of ~1‰ in the upper 2–3 cm of SM8 occurs in the middle of the 20th Century. Small declining trends in δ^{15}N values are observed in WF3, S3 and S4, with larger changes in BM3 and SM3. These trends commence in the 19th Century and therefore do not indicate any changes in N biogeochemistry concurrent with increased industrialisation in the region associated with Oil Sands activities.

Figure 7 shows the C/N ratios of the sediment material from selected lakes expressed as atomic ratios. The trends in C/N ratio largely exhibit the same patterns as those described for C isotopes above, except for lakes WF3 and CM2. C/N ratios are generally low, ranging from 7–18. These values are within the range expected for lacustrine algae (*ca* 5–8) and C3 land plants (*ca* 16+), but outside the range of values expected for C4 land plants (*ca* 35+). The observed values can therefore be interpreted as mixtures of lacustrine algae and C3 land plant sources, with lower C/N ratios reflecting a greater proportional input from aquatic algae. In the majority of sites there are decreases in the C/N ratio

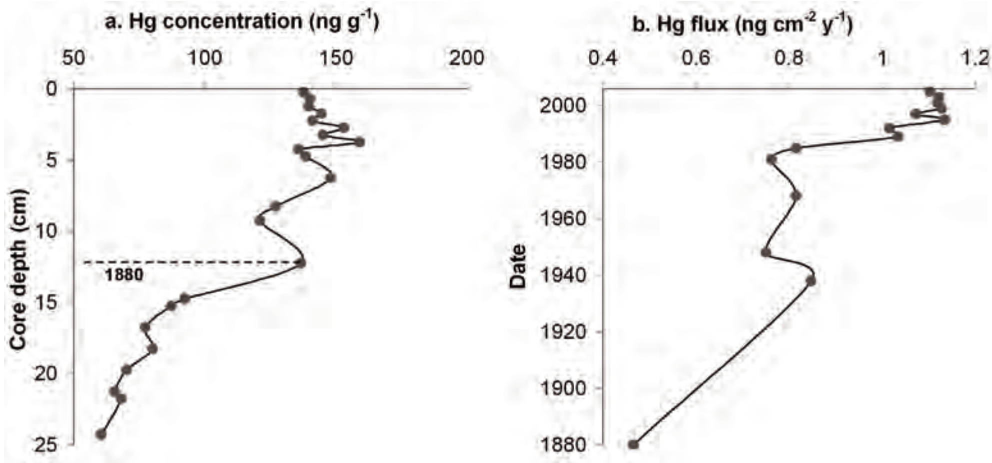

Fig. 8. Concentration and sediment deposition flux of mercury in lake NE7.

suggesting increased contributions from aquatic sources of organic matter.

3.6. Mercury analysis

Mercury concentrations in lake surface sediments varied between 67–138 ng g^{-1} with no obvious spatial pattern (Tab. 1). The highest value occurs in the acidified lake NE7 (core ALB21) and down-core analysis of Hg concentrations at this site show a clear increasing trend from at least the 19th Century to the present (Fig. 8). Mercury flux to the lake sediment also shows a general increase from the 1880s upwards with a sharp increase in the last 20 years, suggesting that the input of Hg into this lake has increased during the historical past. While the long-term trend could be due to increasing global anthropogenic emissions, the recent increase suggests a local input in combination with the recent increase in sedimentation. The recent Hg fluxes reported here are comparable to those reported for Lochnagar in north-east Scotland (Tipping *et al*. 2007), a lake which is known to be impacted by anthropogenic pollution from industrial processes and fossil fuel combustion.

4. DISCUSSION

4.1. Acidification and industrial contamination of lakes in the Oil Sands Region

Only one of the 12 study sites, lake NE7, shows acidification according to diatom analysis. This is the smallest lake studied and one of the shallowest, with the shortest hydrological residence time (see Bennett *et al*. 2008). It is nevertheless chemically comparable to other cored sites which do not show acidification (Tab. 2), e.g., SM6 (core ALB04), SM8 (core ALB03) and WF3 (core ALB11). Instead, these three sites which, like NE7, have pH <6 and alkalinity <100 μeq L^{-1}, show nutrient enrichment according to the diatoms and indeed have higher measured values of TDN and TDP (Tab. 2).

The acidity change in lake NE7 shows that a small pH decline possibly began in the 19th Century but a marked decline occurred after about 1970 when acid indicating species, particularly *Actinella punctata*, began to increase strongly in abundance. Increasing abundances of this and other acidophilous species have been observed in sediment cores elsewhere in Canada (e.g., Dixit & Dickman 1986) where acid deposition has been identified as the cause of lake acidification. Hence, the recent pH history of NE7 seems to be compatible with an acid deposition explanation. There is no evidence of catchment disturbance and possible release of organic acidity from peaty deposits from around the lake and it is noteworthy that unacidified lake WF3 has similar chemistry but a higher mean DOC concentration than NE7. Furthermore, since NE7 is a small (at 11 ha it is the smallest in the data set), shallow, rapidly flushed lake with short residence time and small catchment, the lake system will have limited capacity for in-lake alkalinity generation. With its low alkalinity, all these characteristics make such sites very susceptible to the influence of atmospheric acid deposition (cf. Rudd *et al*. 1986; Kelly *et al*. 1987).

Measured acid deposition inputs to NE7 are however very low and dynamic acidification modelling shows no change in pH (Whitfield *et al*. 2010, this issue). Concentrations of dissolved organic carbon (DOC) in NE7 are amongst the highest of the sites studied leading to a relatively high acid neutralizing capacity (ANC) but low alkalinity (Tab. 2). Although DOC contributes organic buffering and acidity and climatic drivers of increasing DOC have been suggested by some studies (e.g., Freeman *et al*. 2001), there is a widespread trend across North America and northwestern Europe for acid sensitive lakes to show increasing values for both DOC and pH (Monteith *et al*. 2007). The marked pH decline in lake NE7 occurred since around 1970 and the timing is not consistent with changes in nutrient status of some other lakes which are possibly attributable to climatic change. In addition, various datasets from northern Canada show increasing temperatures, especially summer warming, since the 19th Century and palaeolimnological study of a lake in Wood Buffalo National Park found diatom community changes consistent with nutrient enrichment and alkalization over this period (Moser *et al*. 2002). Hence climate-induced increases in organic acidity are unlikely to account for the recent changes in DI-pH at lake NE7.

The main diatom assemblage changes observed in NE7 are coincident with the period of industrial development in the region. Fluxes of mercury to lake sediments at this site have increased in the last 20 years, again suggesting local inputs, but these could be driven by increases in sedimentation rates which, in turn, could have climatic or other drivers. Nevertheless, patterns of Hg accumulation in lake sediments of the Oil Sands Region could warrant further investigation. SCP analysis indicates that there are no major local sources, suggesting that coal and fuel oil combustion are not locally important or if they are used, flue gas emissions are effectively scrubbed of particulates.

4.2. *Other drivers of change in lakes in the Oil Sands Region*

In most of the lakes studied, diatom analysis indicates increasing pH/alkalinity and/or increasing nutrient enrichment. Six of the 12 lakes appear to have experienced increases in DI-pH, including all four lakes west of Fort McMurray and in the Caribou Mountains (Tab. 4). The timing of these increases in DI-pH varies from pre-industrial to very recent. Even more widespread are the increases in nutrient enrichment suggested by the diatoms, observed at all lakes except SM3, NE2 and the acidified site NE7.

Switches to more negative (isotopically lighter) $\delta^{13}C$ values are generally indicative of an increase in or greater abundance of dissolved inorganic carbon (DIC) in the epilimnion, arising from the stronger discrimination against ^{13}C, leading to more negative $\delta^{13}C$ values in algal organic matter. Enriched $\delta^{13}C$ values have been observed with increasing pH associated with a decrease in dissolved CO_2 and increased bicarbonate (e.g., Smith & Walker 1980). Loss of alkalinity associated with atmospheric deposition should lead to the reverse, i.e. more depleted $\delta^{13}C$ values, and the observed $\delta^{13}C$ trend in NE7 matches closely with the observed acidification at this site. Increased delivery of isotopically light DIC/DOC to those lakes exhibiting depletion trends in $\delta^{13}C$ would also result in the observed patterns. However, the changes in $\delta^{13}C$ are small and within the expected depletion (1.4‰) in $\delta^{13}C$ due to fossil fuel combustion (the Suess effect) (Schelske & Hodell 1995).

Overall, the isotope and C/N ratio profiles for the study sites do not show any systematic changes in the biogeochemistry of the lakes that can be attributed to recent Oil Sands activities related to the extraction of oil. Whilst many of the cores show changes in the $\delta^{13}C$ values and C/N ratios in particular, the timing of these changes pre-dates the late 19th Century when emissions of N compounds to the atmosphere were on the increase in the northern hemisphere. The source of organic matter to the lakes has originated, progressively, from greater contributions of aquatic algae. This could be interpreted as a productivity response and is in agreement with observations from the diatom analysis in several of the sites, though there are no signs of increased productivity in the $\delta^{13}C$ values, which would be expected to increase as greater productivity drew down the DIC pool of the lakes. The declining $\delta^{13}C$ values do not preclude an increase in productivity if greater inputs of inorganic carbon to the lakes occurred that were sufficient to offset the draw down of the DIC pool associated with increased productivity. Further work will be required to determine whether this is a plausible scenario.

Changes in sediment $\delta^{15}N$ are inconclusive. Bulk deposition and throughflow samples showed values of $\delta^{15}N\text{-}NO_3^-$ and $\delta^{15}N\text{-}NH_4^+$ in the range –3.3 to +1‰ (B. Mayer, unpublished data). Increasing in-lake utilisation of these N sources might therefore be expected to result in a decline in lake sediment $\delta^{15}N$ from the pre-industrial values of *ca* +1 to +3.5‰, ignoring possible in-lake fractionation effects. However, only a few lakes show declines in bulk sediment $\delta^{15}N$ and several show increases. Most of these changes commenced in the 19th Century and cannot be attributed to N emissions associated with industrial activities in the Oil Sands Region.

The widespread increases in pH/alkalinity and nutrient status suggested by the diatoms and, to a lesser degree the stable isotopes and C:N ratios, are in agreement with earlier observations made by Hazewinkel *et al*. (2008). Possible sources of increasing nutrients are from industrial atmospheric pollution, forest fires or release from soils in the lake catchments. If the latter is shown to be case then it may be that climate warming is having a greater effect on these wilderness lakes than is industrial activity in the region (cf. Moser *et al.* 2002), but the relative importance of climatic change and anthropogenic pollution is not yet known.

5. CONCLUSIONS

The various palaeolimnological analyses described here indicate that acidification does not appear to be a widespread problem in northern Alberta and largely support the conclusions of Hazewinkel *et al*. (2008). However, we do present the first evidence for one site with a significant, recent acidification (lake NE7). This is one of the smallest and shallowest of the sites studied with a peaty catchment, and it is possible that lakes of a similar type are the most vulnerable to the potentially acidifying impacts of deposition arising from the Oil Sands extraction activities.

In addition to identifying the first clearly acidified lake in the region, a key finding from this work concerns the evidence for widespread nutrient enrichment in the region's lakes. While some changes in the sedimentary diatom records are indicative of nutrient enrichment that began in the early 19th Century, suggesting longer-term drivers such as climate, stronger enrichment signals were recorded for the last 20–30 years. Diatom analysis of the twelve cores clearly indicates that the majority of lakes investigated are far from stable and are currently undergoing ecological changes as a result of 20th Century processes.

The causes of lake ecosystem instability in the region are currently unclear. Climate change and nutrient enrichment are probably involved as well as air pollution. Separating species responses to climate warming and air pollution is difficult due to interactions of both potential drivers of lake ecosystem change, but different components of lake communities may show distinctive responses to both drivers. Given the relatively high phosphorus concentrations in some of the region's lakes, it remains a possibility that NO_x emissions and N deposition could also be resulting in changes to lake nutrient status which merit further study. An assessment of the nutrient limitation characteristics of the region's lakes, especially in terms of phytoplankton productivity and diatom species changes, could provide vital information on lake vulnerability to eutrophication caused by N deposition. Furthermore, separating the relative importance of climatic change and anthropogenic pollution in causing some of the changes in unacidified lakes requires further study of other components of lake biota with distinctive sensitivities to climate or nutrient dynamics.

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REFERENCES

Appleby, P.G. 2001. Chronostratigraphic techniques in recent sediments. In: W.M. Last & J.P. Smol (Eds), *Tracking Environmental Change Using Lake Sediments. Vol. 1: Basin Analysis, Coring, and Chronological Techniques*. Kluwer Academic Publishers, Dordrecht, The Netherlands: 171–203.

Battarbee, R.W., R.J. Flower, A.C. Stevenson & B. Rippey. 1985. Lake acidification in Galloway: a palaeoecological test of competing hypotheses. *Nature*, 314: 350–352.

Battarbee, R.W., B.J. Mason, I. Renberg & J.F. Talling (Eds). 1990. *Palaeolimnology and lake acidification*. The Royal Society, London: 219 pp.

Battarbee, R.W., V.J. Jones, R.J. Flower, N.G. Cameron, H. Bennion, L. Carvalho & S. Juggins. 2001. Diatoms. In: J.P. Smol, H.J.B. Birks & W.M. Last (Eds), *Tracking environmental change using lake sediments. Volume 3. Terrestrial, algal, and siliceous indicators*. Kluwer Academic Publishers, Dordrecht, The Netherlands: 155–202.

Bennett, K.E., J.J. Gibson & P.M. McEachern. 2008. Water-yield estimates for critical loadings assessment: comparisons of gauging methods versus an isotopic approach. *Can. J. Fish. Aquat. Sci*., 65: 83–99.

Birks, H.J.B., J.M. Line, S. Juggins, A.C. Stevenson & C.J.F. ter Braak. 1990. Diatoms and pH reconstruction. *Phil. Trans. R. Soc. Lond. Ser. B*, 327: 263–278.

Camburn, K.E. & D.F. Charles. 2000. *Diatoms of low alkalinity lakes in the United States*. Scientific Publication 18. The Academy of Natural Sciences, Philadelphia: 152 pp.

Charles, D.F. (Ed.) 1991. *Acidic deposition and aquatic ecosystems: regional case studies*. Springer Verlag New York Inc., New York: 747 pp.

Curtis, C.J., T.E.H. Allott, M. Hughes, J. Hall, R. Harriman, R. Helliwell, M. Kernan, B. Reynolds & J. Ullyett. 2000. Critical loads of sulphur and nitrogen for freshwaters in Great Britain and assessment of deposition reduction requirements with the First-order Acidity Balance (FAB) model. *Hydrol. Earth Syst. Sci*., 4: 125–140.

Curtis, C.J., I. Botev, L. Camarero, J. Catalan, D. Cogalniceanu, M. Hughes, M. Kernan, J. Kopáček, A. Korhola, R. Psenner, M. Rogora, E. Stuchlík, M. Veronesi & R.F. Wright. 2005. Acidification in European mountain lake districts: a regional assessment of critical load exceedance. *Aquat. Sci*., 67: 237–251.

Curtis, C., R. Flower, N. Rose, J. Shilland, G. Simpson, S. Turner, H. Yang & S. Pla. 2009. *Palaeolimnological study of selected lakes in the Wood Buffalo Region involving collection and analysis of surface, bottom and full core lake sediment samples*. Final Project Report 2008, CEMA Contract 2008-0004. ECRC Research Report No. 132, ECRC, London: 79 pp.

Dixit, S.S. & M.D. Dickman. 1986. Correlation of surface sediment diatoms with the present lake water pH in 28 Algoma lakes, Ontario, Canada. *Hydrobiologia*, 131: 133–143.

Dixit, S.S., B.F. Cumming, H.J.B. Birks, J.P. Smol, J.C. Kingston, A.J. Uutata, D.F. Charles & K.E. Camburn. 1993. Diatom assemblages from Adirondack lakes (New York, USA) and the development of inference models for retrospective environmental assessment. *J. Paleolimnol*., 8: 27–47.

Flower, R.J. 2005. A taxonomic and ecological study of diatoms from freshwater habitats in the Falkland Islands. *Diatom Res*., 20: 23–96.

Flower, R.J. & R.W. Battarbee. 1983. Diatom evidence for recent acidification of two Scottish lochs. *Nature*, 305: 130–133.

Freeman, C., C.D. Evans, D.T. Monteith, B. Reynolds & N. Fenner. 2001. Export of organic carbon from peat soils. *Nature*, 412: 785.

Gavin, D.G., W.W. Oswald, E.R. Wahl & J.W. Williams. 2003. A statistical approach to evaluating distance metrics and analog assignments for pollen records. *Quat. Res*., 60: 356–367.

Hazewinkel, R.R.O., A.P. Wolfe, S. Pla, C. Curtis & K. Hadley. 2008. Have atmospheric emissions from the Athabasca Oil Sands acidified lakes in northeastern Alberta, Canada? *Can. J. Fish. Aquat. Sci*., 65: 1554–1567.

Henriksen, A., J. Kämäri, M. Posch & A. Wilander. 1992. Critical loads of acidity: Nordic surface waters. *Ambio*, 21: 356–363.

Henriksen, A., B.L. Skjelkvåle, J. Mannio, A. Wilander, R. Harriman, C. Curtis, J.P. Jensen, E. Fjeld & T. Moiseenko. 1998. Northern European Lake Survey - 1995: Finland, Norway, Sweden, Denmark, Russian Kola, Russian Karelia, Scotland and Wales. *Ambio*, 27: 80–91.

Hohn, M.H. & J. Hellerman. 1963. The taxonomy and structure of diatom populations from three eastern north American rivers using three sampling methods. *Trans. Am. Microsc. Soc*., 82: 250–329.

Jeffries, D.S. 1997. *1997 Canadian acid rain assessment, Volume 3: the effects on Canada's lakes, rivers and wetlands*. Environment Canada, Ottawa, Ontario.

Jeffries, D.S., T.A. Clair, S. Couture, P.J. Dillon, J. Dupont, W. Keller, D.K. McNicol, M.A. Turner, R. Vet & R. Weeber. 2003. Assessing the recovery of lakes in southeastern Canada from the effects of acidic deposition. *Ambio*, 32: 176–182.

Kämäri, J., M. Forsius, P. Kortelainen, J. Mannio & M. Verta. 1991. Finnish lake survey: present status of acidification. *Ambio*, 20: 23–37.

Kelly, C.A., J.W.M. Rudd., R.H. Hesslein, D.W. Schindler, P.J. Dillon, C.T. Driscoll, S.A.Gherini & R.E. Hecky. 1987. Prediction of biological acid neutralization in acid sensitive lakes. *Biogeochem.*, 3: 129–140.

Krammer, K. & H. Lange-Bertalot. 1986. *Bacillariophyceae. 1. Teil: Naviculariaceae. Susswasser Flora von Mitteleuropa*. H. Ettl, J. Gerloff, H. Heynig & D. Mollenhauer (Eds). Gustav Fischer Verlag, Stuttgart: 876 pp.

Krammer, K. & H. Lange-Bertalot. 1988. *Bacillariophyceae. 2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. Susswasser Flora von Mitteleuropa.* H. Ettl, J. Gerloff, H. Heynig & D. Mollenhauer (Eds). Gustav Fischer Verlag, Stuttgart: 576 pp.

Krammer, K. & H. Lange-Bertalot. 1991. *Bacillariophyceae. 4. Teil: Achnanthaceae Kritische Erganzungen zu Navicula (Lineolatae). und Gomphonema. Susswasser Flora von Mitteleuropa*. H. Ettl, J. Gerloff, H. Heynig & D. Mollenhauer (Eds). Gustav Fischer Verlag, Stuttgart: 576 pp.

Lange-Bertalot, H. & K. Krammer. 1989. *Achnanthes eine Monographie der Gattung. Bibliotheca Diatomologica*, vol. 18. J. Cramer, Berlin & Stuttgart: 393 pp.

Monteith, D.T., J.L. Stoddard, C.D. Evans, H.A. de Wit, M. Forsius, T. Hogasen, A. Wilander, B.L. Skjelkvale, D.S. Jeffries, J. Vuorenmaa, B. Keller, J. Kopacek & J. Vesely. 2007. Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. *Nature*, 450: 537–541.

Moser, K.A., J.P. Smol, G.M. MacDonald & C.P.S. Larsen. 2002. 19th Century eutrophication of a remote boreal lake: a consequence of climate warming? *J. Paleolimnol*., 28: 269–281.

Overpeck, J.T., T. Webb III & I.C. Prentice. 1985. Quantitative interpretation of fossil pollen spectra – dissimilarity coefficients and the methodology of modern analogs. *Quat. Res*., 23: 87–108.

Patrick, R. & C.W. Reimer. 1966–1977. *The Diatoms of the United States exclusive of Alaska and Hawaii*. Vols 1 & 2, Monograph 13, The Academy of Natural Sciences of Philadelphia.

Pelley, J. 2006. Acid rain worries in western Canada. *Environ. Sci. Technol*., 40: 5830.

Pla, S. & C. Curtis. 2006. Lake sediment core top analysis. Report prepared for the CEMA NO_x SO_x Management Working Group under Contract Number 2005-0038. Ensis, London: 9 pp.

Pla, S., C. Curtis & G. Simpson. 2006. *Lake sediment core bottom sample analysis and assessment of diatom change*. Report prepared for the CEMA NOx SOx Management Working Group under Contract Number 2006-0020. Ensis, London: 11 pp.

Pla, S., D. Monteith, R.J. Flower & N. Rose. 2009. The recent palaeolimnology of a remote Scottish loch with special reference to the relative impacts of regional warming and atmospheric contamination. *Freshwat. Biol*., 54: 505–523.

RAMP. 2007. Regional Aquatics Monitoring Programme Final 2006 Technical Report. Prepared for the RAMP Steering Committee, Edmonton, Canada. Available from www.ramp-alberta.org/.

RAMP. 2008. Regional Aquatics Monitoring Programme Final 2007 Technical Report. Prepared for the RAMP Steering Committee, Edmonton, Canada. Available from www.ramp-alberta.org/.

Renberg, I. & H. Hansson. 2008. The HTH sediment corer. *J. Paleolimnol*., 40: 655–659.

Rose, N.L. 1994. A note on further refinements to a procedure for the extraction of carbonaceous fly-ash particles from sediments. *J. Paleolimnol*., 11: 201–204.

Rose, N. 2001. Fly-ash particles. In: W.M Last & J.P. Smol (Eds), *Tracking environmental change using lake sediments*. Volume 2: Physical & Geochemical Methods. Kluwer Academic Publishers, Dordrecht, The Netherlands: 319–349.

Rose, N.L. 2008. Quality control in the analysis of lake sediments for spheroidal carbonaceous particles. *Limnol. Oceanogr. Methods*, 6: 172–179.

Rudd, J.W.M., C.A. Kelly, V. St. Louis, R.H. Hesslein, A. Furutani & M.H. Holoka. 1986. Microbial consumption of nitric and sulfuric acids in acidified north temperate lakes. *Limnol. Oceanogr*., 31: 1267–1280.

Schelske, C.L. & D.A. Hodell. 1995. Using carbon isotopes of bulk sedimentary organic matter to reconstruct the history of nutrient loading and eutrophication in Lake Erie. *Limnol*. *Oceanogr*., 40: 918–929.

Schindler, D. 1988. Effects of acid rain on freshwater ecosystems. *Science*, 239: 149–157.

Schindler, D. 1998. A dim future for boreal waters and landscapes. *BioScience*, 48:157–164.

Siver, P.A., P.B. Hamilton, K. Stachura-Suchoples & J.P. Kociolek. 2005. Diatoms of North America: the freshwater flora of Cape Cod. Iconographia Diatomologica, 14: 463 pp.

Smith, F.A. & N.A. Walker. 1980. Photosynthesis by aquatic plants: effects of unstirred layers in relation to assimilation of CO_2 and HCO_3– and to carbon isotopic discrimination. *New Phytol*., 86: 245–259.

Smol, J.P., R.W. Battarbee, R.B. Davis & J. Merilainen. 1986. *Diatoms and lake acidity: reconstructing pH from siliceous algal remains in lake sediments*. W. Junk, Dordrecht, The Netherlands: 308 pp.

Stoddard, J.L., D.S. Jeffries, A Lükewille, T.A. Clair, P.J. Dillon, C.T. Driscoll, M. Forsius, M. Johannessen, J.S. Kahl, J.H. Kellogg, A. Kemp, J. Mannio, D.T. Monteith, P.S. Murdoch, S. Patrick, A. Rebsdorf, B.L. Skjelkvåle, M.P. Stainton, T.Traaen, H. van Dam, K.E. Webster, J. Wieting & A. Wilander. 1999. Regional trends in aquatic recovery from acidification in North America and Europe. *Nature*, 401: 575–578.

ter Braak, C.J.F., S. Juggins, H.J.B. Birks & H. van der Voet. 1993. Weighted averaging partial least squares regression (WA-PLS): Definition and comparison with other methods for species-environment calibration. In: G.P. Patil & C.R. Rao (Eds), *Multivariate Environmental Statistics*, Elsevier: 525–560.

Tipping, E., H. Yang, A. Lawlor, N.L. Rose & L. Shotbolt. 2007. Trace metals in the catchment, loch and sediments of Lochnagar: measurements and modelling. In: N.L. Rose (Ed.), Lochnagar: *The Natural History of a mountain lake. Developments in palaeoenvironmental research*. Vol. 12, Springer: 345–373.

Whitfield, C.J., J. Aherne, P.J. Dillon & S.A. Watmough. 2007. Modelling acidification, recovery and target loads for headwater catchments in Nova Scotia, Canada. *Hydrol. Earth Syst. Sci*., 11: 951–963.

Whitfield, C.J., J. Aherne, B.J. Cosby & S.A. Watmough. 2010. Modelling boreal lake catchment response to anthropogenic acid deposition. *J.Limnol*., 69(Suppl. 1): 135-146. DOI: 10.3274/JL10-69-S1-14.

Whole-ecosystem study shows rapid fish-mercury response to changes in mercury deposition

Reed C. Harris[a], John W. M. Rudd[b,c], Marc Amyot[d], Christopher L. Babiarz[e], Ken G. Beaty[f], Paul J. Blanchfield[f], R. A. Bodaly[g], Brian A. Branfireun[h], Cynthia C. Gilmour[i], Jennifer A. Graydon[j], Andrew Heyes[k], Holger Hintelmann[l], James P. Hurley[e], Carol A. Kelly[c], David P. Krabbenhoft[m], Steve E. Lindberg[n], Robert P. Mason[o], Michael J. Paterson[f], Cheryl L. Podemski[f], Art Robinson[p], Ken A. Sandilands[f], George R. Southworth[n], Vincent L. St. Louis[j], and Michael T. Tate[m]

[a]Tetra Tech Inc., 180 Forestwood Drive, Oakville, ON, Canada L6J 4E6; [c]R&K Research Inc., 675 Mt. Belcher Heights, Salt Spring Island, BC, Canada V8K 2J3; [d]Département de Sciences Biologiques, Université de Montréal, C.P. 6128, Succ. Centre-Ville, Montréal, QC, Canada H3C 3J7; [e]Environmental Chemistry and Technology Program, University of Wisconsin, 660 North Park Street, Madison, WI 53706; [f]Freshwater Institute, Fisheries and Oceans Canada, 501 University Crescent, Winnipeg, MB, Canada R3T 2N6; [g]Penobscot River Mercury Study, 115 Oystercatcher Place, Salt Spring Island, BC, Canada V8K 2W5; [h]Department of Geography, University of Toronto , South Building, 3359 Mississauga Road, North Mississauga, ON, Canada L5L 1C6; [i]Smithsonian Environmental Research Center, P.O. Box 28, 647 Contees Wharf Road, Edgewater, MD 21037; [j]Department of Biological Sciences, University of Alberta, Edmonton, AB, Canada T6G 2E9; [k]Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, University of Maryland, P.O. Box 38, Solomons, MD 20688-0038; [l]Department of Chemistry, Trent University, 1600 West Bank Drive, Peterborough, ON, Canada K9J 7B8; [m]U.S. Geological Survey, 8505 Research Way, Middleton, WI 53562 ; [n]Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN 37831-6036; [o]Department of Marine Sciences, University of Connecticut, 1080 Shennecossett Road, Groton, CT 06340; and [p]Canadian Forest Service, 1219 Queen Street East, Sault St. Marie, ON, Canada P6A 5M7

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Methylmercury contamination of fisheries from centuries of industrial atmospheric emissions negatively impacts humans and wildlife worldwide. The response of fish methylmercury concentrations to changes in mercury deposition has been difficult to establish because sediments/soils contain large pools of historical contamination, and many factors in addition to deposition affect fish mercury. To test directly the response of fish contamination to changing mercury deposition, we conducted a whole-ecosystem experiment, increasing the mercury load to a lake and its watershed by the addition of enriched stable mercury isotopes. The isotopes allowed us to distinguish between experimentally applied mercury and mercury already present in the ecosystem and to examine bioaccumulation of mercury deposited to different parts of the watershed. Fish methylmercury concentrations responded rapidly to changes in mercury deposition over the first 3 years of study. Essentially all of the increase in fish methylmercury concentrations came from mercury deposited directly to the lake surface. In contrast, <1% of the mercury isotope deposited to the watershed was exported to the lake. Steady state was not reached within 3 years. Lake mercury isotope concentrations were still rising in lake biota, and watershed mercury isotope exports to the lake were increasing slowly. Therefore, we predict that mercury emissions reductions will yield rapid (years) reductions in fish methylmercury concentrations and will yield concomitant reductions in risk. However, a full response will be delayed by the gradual export of mercury stored in watersheds. The rate of response will vary among lakes depending on the relative surface areas of water and watershed.

bioaccumulation | mercury methylation | stable isotopes | whole-ecosystem experimentation | methylmercury

Industrial activities have increased atmospheric mercury deposition and global mercury contamination ≈3-fold since preindustrial times (1). Some of this deposited mercury is converted by bacteria to methylmercury, a highly toxic form that bioaccumulates through food webs. In thousands of lakes in North America, Europe, and Asia, methylmercury contamination of fish negatively impacts the health of humans and wildlife, causes financial losses to commercial and sport fisheries, and affects those traditional ways of life in which fish are consumed as primary foods (2–5). This issue has now approached a critical juncture because many nations (e.g., the United States and Canada) and organizations (e.g., United Nations Environment Program) are debating the implementation and extent of mercury emission controls. One of the reasons for this debate is that it has been notoriously difficult to establish how annual and regional patterns of mercury loading via deposition influence fish methylmercury concentrations (6). This is because the effects of mercury deposition alone are obscured by various factors [including climate change (7), lake acidification (8), and land use (9–11)] that act synergistically to influence fish methylmercury concentrations. In addition, there is reason to believe that reductions in atmospheric mercury deposition due to emission controls might not be reflected very quickly in lowered levels of methylmercury in fish: there are many decades of prior mercury deposition stored in lakes and watersheds that may continue to be methylated and bioaccumulated even after deposition rates are reduced. However, if contemporary mercury loadings are the more important for methylation, then a change in loading should be reflected in fish relatively quickly. As a result of these uncertainties, it has been impossible, until now, to predict how quickly fish mercury concentrations would change if and when atmospheric mercury loadings are reduced.

To overcome the complications described above, we combined two unique experimental approaches. First, manipulation of an entire catchment (a lake and its watershed) was used to examine the impacts of mercury loadings at the whole-ecosystem scale. This scale was necessary because mercury works its way through catchments in many steps that interact with each other in ways that are not completely understood: beginning with deposition

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Abbreviations: ELA, experimental lakes area; ICP, inductively coupled plasma.

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[b]To whom correspondence should be addressed: E-mail: john_rudd@gulfislandswireless.com.

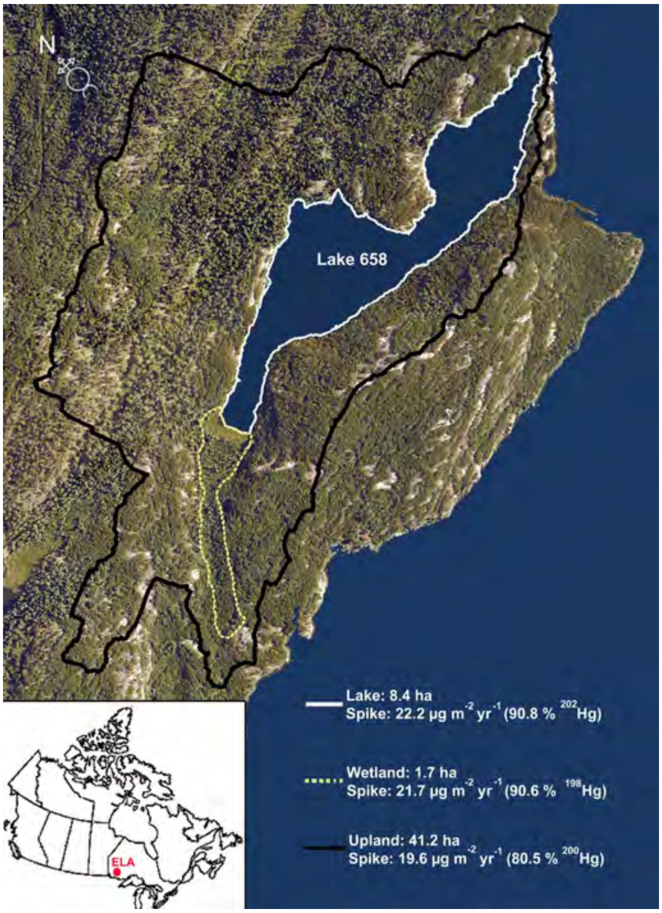

Fig. 1. Three-year average isotopic mercury addition rates (2001–2003) to the upland, wetland, and lake surfaces of the Lake 658 ecosystem at the ELA, northwestern Ontario. The target rate was 22 μg·m^{-2}·year^{-1}. The average actual addition rate for the whole catchment was 20.1 μg·m^{-2}·year^{-1}, which was 6 times the average wet deposition to this site (3.2 μg·m^{-2}·year^{-1}) over the same period.

onto vegetation and soils, mercury is mobilized into streams, methylated in a variety of different habitats within an ecosystem, and then bioaccumulates through complex food webs. Thus, the real-world predictive value of laboratory-scale and mesocosm experiments is limited. Second, the addition of enriched stable mercury isotopes enabled us to follow newly deposited mercury separately from mercury that was already in the catchment. This experiment made it possible to measure the magnitude of change in fish methylmercury concentrations due solely to changes in mercury input and to examine how quickly methylmercury concentrations in fish change in response to alterations in annual mercury loading.

The Mercury Experiment to Assess Atmospheric Loading in Canada and the United States (METAALICUS) is being conducted in the Lake 658 catchment at the Experimental Lakes Area (ELA), northwestern Ontario (Fig. 1), where wet deposition of mercury is low compared with other more contaminated sites in Europe and the United States (refs. 1 and 12 and Fig. 1). Here, inorganic mercury load to an entire catchment could be experimentally increased to levels experienced in more polluted regions (1) by adding mercury in the form of three highly enriched stable isotopes. Because the wetland, upland, and lake portions of the ecosystem were expected to respond differently to mercury loadings, study of the catchment was partitioned into these three compartments, and a different isotope was added to each one. Specifically, wetlands and lake sediments are sites of intense mercury methylation, and uplands are important contributors of inorganic mercury to lakes (13, 14). In upland and wetland areas, isotopic mercury (referred to as upland spike and wetland spike) was added by fixed wing aircraft once each year for 3 years (2001–2003). Lake spike was added by boat every 2 weeks during the open-water season (Fig. 1). In this paper, the term "ambient mercury" refers to all mercury that is not spike mercury. In ELA catchments, most of the mercury is atmospheric in origin, with ≈1% estimated to come from geologic weathering (15). Here, we describe results of the first 3 years of mercury additions.

Results and Discussion

After 3 years, all of the mercury spikes were still moving from their points of application, the vegetation and surface water, to soils and sediments, which are the dominant sites of long-term mercury accumulation in ecosystems (Table 1). In the upland, the areal mass of ambient mercury was much greater in the soil than in vegetation, whereas spike mercury was only slightly greater in the soil. In the wetland, ambient mercury was likewise much greater in the peat than in vegetation, whereas spike mercury had the opposite distribution, being more predominant in vegetation than in peat. In the lake, both spike and ambient mercury masses were greater in the sediments than in the water, but the contrast was much less for spike mercury (Table 1).

Throughout this article, the effects of spike additions are expressed as the percentage increase in mercury or methylmercury that resulted from the added isotopic form [(spike mercury/ambient mercury) × 100]. For the large soil, peat, and sediment pools, the percentage increases over 3 years were small (2–5%; see Table 1).

Although spike export via runoff from upland and wetland to the lake was minimal, both areas yielded substantial amounts of ambient mercury (Fig. 2). In fact, the quantity of upland spike observed in runoff, although detectable, was ≈100 times less than the amounts of ambient mercury (Fig. 2*a*). This ratio in runoff was similar to the ratio of spike to ambient mercury concentrations observed in watershed soils (Table 1). The amount of wetland spike exported was below the level of detection (Fig. 2*b*). Thus, after 3 years of loading, most of the spike mercury remained bound to vegetation and soils, and ≈99% of the mercury in runoff was older, preexisting ambient mercury. A similar result was seen in a pilot study on an upland microcatchment (16) in which spike mercury worked its way into the soils and was incorporated into the much larger preexisting pool of soil mercury before exiting the catchment.

Although the increase of mercury exported to Lake 658 due to spike additions to upland areas of the catchment was insignificant, it became larger each year (0.1% in 2001, 0.3% in 2002, and 0.6% in 2003) and therefore is expected to increase further with continued loading. Over the long term (centuries), historical data suggest that watershed export of mercury may respond proportionately to changes in atmospheric mercury (17, 18).

Because upland and wetland mercury exports were essentially unchanged (<1%) by spike additions, the only significant increase in mercury loading to the lake occurred as a result of spike additions directly to the lake itself. In fact, lake spike constituted the single largest input of mercury to the lake (Fig. 3). The next largest input was old ambient mercury from the uplands, followed by wet deposition of ambient mercury and old ambient mercury from the wetland (Fig. 3). Ambient mercury inputs actually decreased from 2001 to 2003 due to natural variations in rainfall and stream flow that resulted in corresponding changes in ambient mercury runoff. Overall, the spike applications increased the average annual mercury load to the lake by 120%.

Essentially, all mercury in fish is methylmercury (19), produced by anaerobic bacteria acting on inorganic mercury before

Table 1. Concentrations, masses, and standard errors of ambient and spike total mercury in catchment compartments and percent increases due to 3 years of spike additions

		THg concentrations, ng·gDW^{-1} or ng·liter^{-1}		Areal mass of THg, μg·m^{-2}		
Catchment compartment	No. of sites	Ambient	Spike	Ambient	Spike	Percent increase due to spike after 3 years
Upland						
Canopy	20	16.0 ± 1.3	3.6 ± 0.6	17.3 ± 2.3	3.6 ± 0.6	21
Ground vegetation	20	87.6 ± 6.8	13.8 ± 2.4	84.7 ± 13	13.9 ± 4.1	16
Soil	88	160 ± 19.1	3.8 ± 0.47	960	23	2.4
Total				1,060	40	3.7
Wetland						
Canopy	3	17.2 ± 1.1	6.3 ± 3.1	9.9 ± 1.1	4.2 ± 2.6	42
Ground vegetation	3	49.0 ± 4.9	37.2 ± 11.4	37.2 ± 6.9	32.9 ± 17	88
Peat, 0–5 cm	16	81.5 ± 8.8	2.8 ± 0.5	326	11	3.4
Total				373	48	13
Lake						
Water column	1	1.73	0.94	12	6.3	53
Sediments, 0–5 cm	11	472 ± 94	20.8 ± 3.3	460 ± 45	23 ± 3.7	5
Total				470	29	6

For the canopy, vegetation masses exclude tree boles. The depths of soil, peat, and sediment chosen were based on the depth of penetration of spike mercury after 3 years. For upland soils, this was the entire soil column. For peat and the lake sediments, this was the upper 5 cm. The total spike amounts, per meter squared, were 68%, 74%, and 45% of the spike applications over 3 years to the upland, wetland, and lake (Fig. 1), respectively. Independent measurements found that 25–30% of upland and wetland spikes (unpublished data) and 45% of the lake spikes (37) were lost through evasion to the atmosphere. An additional 5% of lake spike was lost through the lake outflow. Thus, all of the spike applied could be accounted for within the uncertainties of the measurements. gDW, grams dry weight.

it bioaccumulates in food webs. The most intense sites of methylmercury production in ecosystems are in wetlands, lake sediments, and anoxic bottom waters (13, 20). In the Lake 658 catchment, the wetland exported ambient methylmercury at a rate of 0.2–0.4 μg·m^{-2}·year^{-1}, which is at the high end of the range of methylmercury export rates from wetlands at the ELA (14). However, this was all older, ambient methylmercury. Most of the wetland spike was still bound to the vegetation and moss well above the water table in the wetland and hydrologically disconnected from the saturated anoxic zone where methylation occurs. Such a low level of new mercury export and methylation would not be expected to occur in all wetlands, however. For example, in a pilot study (21) of a wetland fringing ELA Lake 115, which has a water table near the peat surface, added spike mercury was quickly methylated and transported into the lake. Thus, some types of wetlands could export newly deposited mercury and thereby impact fish mercury concentrations on a much shorter time scale than was the case for the Lake 658 wetland.

Some of the spike added directly to the lake was transported rapidly to sites of methylation in sediments and anoxic bottom waters. Methylated lake spike was found in the anoxic bottom

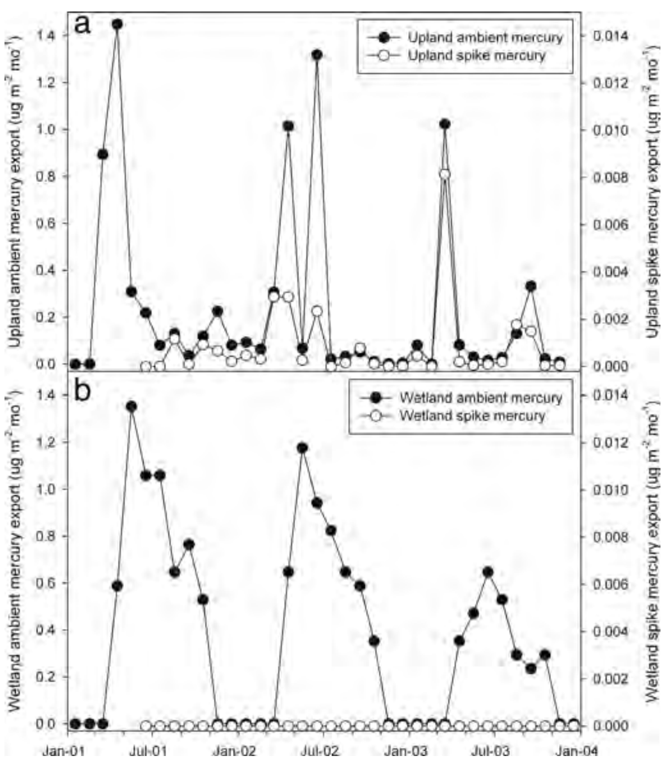

Fig. 2. Mean monthly export of ambient and spike total mercury per square meter of upland and wetland areas.

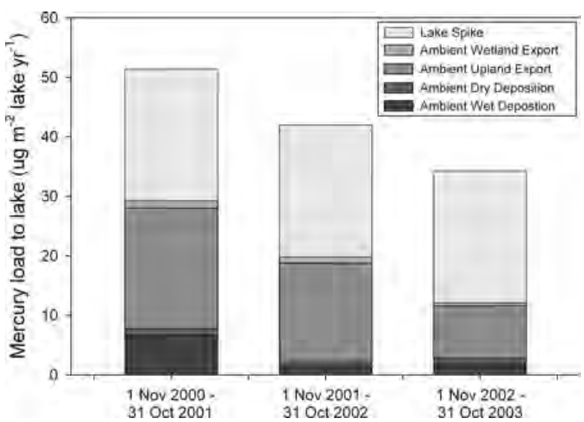

Fig. 3. Annual loadings of spike and ambient mercury to Lake 658 per square meter of lake surface.

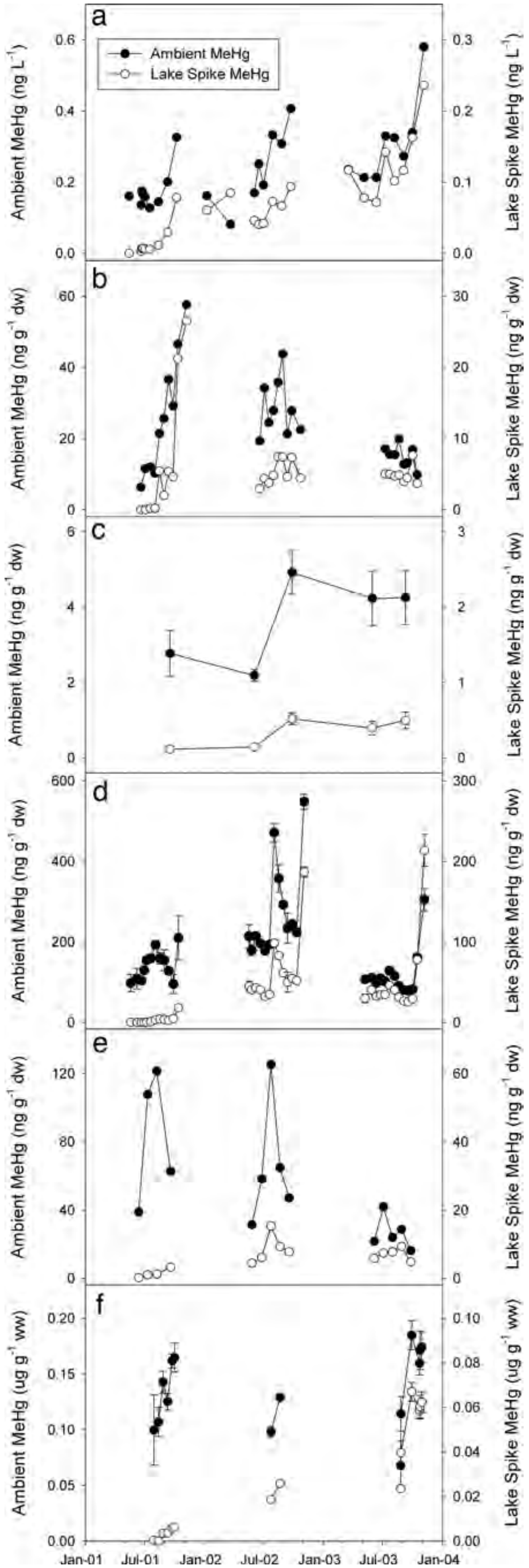

Fig. 4. Concentrations of lake spike and ambient methylmercury (MeHg) in water (*a*), sediment trap material (*b*), the top 2 cm of sediments (*c*), zooplankton (*d*), *H. azteca* (*e*), and young-of-the-year (YOY) yellow perch muscle samples (*f*) during 3 years of mercury spike additions to Lake 658 and its watershed. The perch data were measured as total mercury with the assumption that almost all mercury in fish muscle is methylmercury (19). Vertical bars are standard errors.

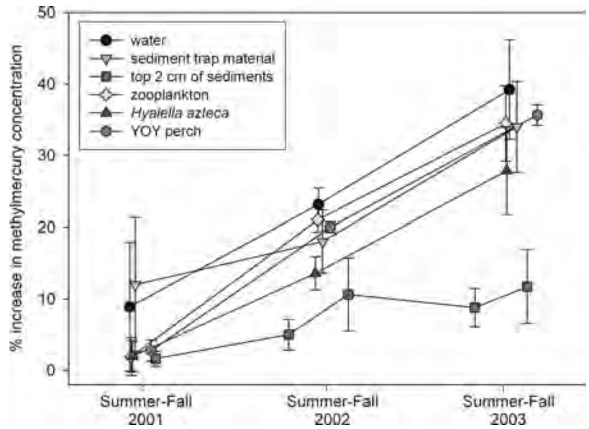

Fig. 5. Percentage increase of methylmercury concentrations in water, sediment trap material, top 2 cm of sediments, and biota resulting from additions of lake spike mercury to Lake 658 over a 3-year period. Vertical bars are standard deviations on the seasonal means. All trends were significantly linear with time ($P < 0.05$), except for the sediment traps and zooplankton.

waters (at a concentration of 0.014 ng·liter^{-1}) 3 days after first being added to the surface water (Fig. 4*a*). It was found in sediment traps below the thermocline 2–4 weeks after the first lake spike additions (Fig. 4*b*). After 1 month, methylated lake spike was found in sediments, zooplankton, and benthos (*Hyalella azteca*) (Fig. 4 *c*, *d*, and *e*, respectively), and within 2 months, it was found in several fish species in Lake 658 (22), including young-of-the-year yellow perch (Fig. 4*f*). In contrast, upland spike was not detected in benthos or fish until the third year of additions and even then was not present in quantifiable amounts. Wetland spike was never detected in the biota.

Week-to-week patterns of lake spike and ambient methylmercury concentrations in the lake water, sediments, and food web were remarkably similar (Fig. 4). In all of these compartments, whenever ambient methylmercury concentrations increased or decreased, so did the concentration of lake spike methylmercury. This synchrony means that the same environmental factors that act on the ambient mercury being methylated and bioaccumulated were also acting on the lake spike, and that bioavailable spike mercury behaved like bioavailable ambient mercury.

There was year-to-year variability in concentrations of both ambient and spike methylmercury in all lake compartments (Fig. 4). Annual variation in methylmercury concentration is driven by environmental factors [e.g., temperature, pH (8, 23)] that affect methylation rates. Although this natural variability has confounded earlier attempts to isolate the effect of mercury loading in ecosystems, the use of enriched stable isotopes allowed us to follow spike methylmercury separately from ambient methylmercury. Thus, we were able to determine the increase in methylmercury that was due solely to the lake spike additions. In all compartments of the lake, the percent increase in methylmercury due to the lake spike increased approximately linearly with time (Fig. 5). The rates of increase were very similar in the water, the sediment trap material, and the biota, including fish (Fig. 5). The fractional rate of increase was slower in sediments, likely because lake spike mercury was more diluted in the top 2 cm of sediment, which contains ≈20 years of mercury deposition.

These data (Fig. 5) clearly show an annual, cumulative increase in methyl mercury bioaccumulation in response to the continuing experimental additions of inorganic mercury to the lake. By the end of the third year of additions, concentrations of methylmercury in water and biota were 30–40% higher than they would have been if the lake spike had not been added.

The contribution of lake spike to the methylmercury pools was greater each year (Fig. 5), even though the quantity of lake spike mercury added was the same each year. This could happen only if the inorganic mercury pool being methylated contained >1 year's worth of mercury inputs. This finding has implications for the response times of lakes to changes in mercury inputs.

The 30–40% increase in methylmercury in biota was much less than the 120% increase in inorganic mercury loading to the lake (Fig. 3). Previous studies have shown that, on the short term, there is a proportional response of rates of production (24, 25) and bioaccumulation (26) of new methylmercury to new additions of inorganic mercury. However, when new mercury is added to a system that already contains older inorganic mercury, both the new and older mercury contribute to methylation (although not necessarily equally), so on the short term the overall rate of mercury methylation (new + old) does not respond in direct proportion to the amount of new mercury added. This is why the increases in methylmercury in the first 3 years (30–40%) were much less than the increase in loading rate (Fig. 5).

We do not know yet whether there will be a proportional response to the continuing increased loading to the lake in the longer term, as suggested by some regional studies (6). For example, if mercury demethylation switched on at some increased concentration of sediment methylmercury, the end response would not be directly proportional to the increase in inorganic mercury loading.

The percentage increase in methylmercury has obviously not yet reached a plateau (Fig. 5), indicating that the ecosystem is not yet in steady state. This may not happen for a decade or more (27). Thus, our data show that even the most responsive compartment of the catchment (the lake) was not yet at a new steady state, and the terrestrial compartments will take substantially longer to achieve such a state. We expect that, in the long term, the full effect of the increased mercury loading will be much larger than the 30–40% increase in methylmercury in the biota that was evident after only 3 years.

Conclusions

Our experiment showed that an increase in mercury loading at rates relevant to atmospheric deposition resulted in an increase in methylmercury production and concentrations in aquatic biota in only 3 years. As emission controls are instituted and atmospheric mercury deposition decreases, there could be some hysteresis in how lakes respond to decreased mercury loading. However, this would not change the expectation that a decrease in atmospheric mercury deposition would lower fish mercury concentrations. Typically, lakes that receive all of their mercury from the atmosphere (such as perched seepage lakes) could be expected to respond in approximately a decade. For all other lakes, which receive at least some of their mercury load from the watershed, as well as a portion directly from the atmosphere, we would expect multiphased responses to a reduction in input: (*i*) an initial rapid decline in the mercury content of fish as a result of reduced direct deposition to the lake, followed by (*ii*) responses from the wetland and the upland, which will be prolonged declines (taking up to centuries) driven by reequilibration of the wetland peat and upland soils. Elucidation of this multiphased response advances our understanding of how anticipated reductions in atmospheric mercury emissions will affect fish methylmercury concentrations in lakes, predicting not only that there will be a benefit but also the time scales over which that benefit will be achieved.

Materials and Methods

Site Description. Mercury Experiment to Assess Atmospheric Loading in Canada and the United States (METAALICUS) is being conducted at the ELA, northwestern Ontario (28), on the Lake 658 catchment. Lake 658 is a 13-m-deep, oligotrophic, headwater lake located in the ELA. The lake has an average water residence time of 5 years, pH ≈6.5, dissolved organic carbon ≈9 mg·liter^{-1} and summer anoxia in the bottom 1–2 m of the hypolimnion (29). The terrestrial vegetation is a typical boreal forest with uplands mainly of jack pine, balsam fir, red maple, poplar, and paper birch growing on thin podzolic soils. The sphagnum moss-dominated wetland has an overstory of black spruce and an understory of alder and Labrador tea, leather leaf, and sweet gale.

Spike-Application Methods. The upland and wetland spikes were applied once each year by fixed wing aircraft. $HgNO_3$ spikes were diluted in acidified lake water (pH 4) in a fiberglass tank in the aircraft and then were sprayed onto the terrestrial surfaces by using a stainless steel boom actuated by global-positioning software. Spraying was carried out only immediately before or during a rain event and at wind speeds of <15 km·hr^{-1} to minimize drift. Other application details, including losses of mercury to the equipment and an accounting of these losses, are described elsewhere (29). The net application rates (Fig. 1) to the upland and wetland areas were somewhat different from the target rate (22 μg·m^{-2}·year^{-1}) because of these losses. To prevent spray drift of terrestrial spikes into the lake, a buffer zone of 20 m was left around the shoreline of the lake. This area was sprayed manually with a gas-powered water pump and fire hose (29).

Lake spike additions were done by adding $HgNO_3$ lake spike to four 20-liter carbuoys filled with acidified lake water (pH 4), and dispensed into the propeller wash of an electric outboard motor. Additions were done at dusk to minimize photoreduction and loss of elemental mercury and were done at 2-week intervals over an 18-week period during the ice-free season.

Sampling Methods. During the open-water season, rain was collected into preacidified Teflon containers mounted in an automated precipitation sampler (30). Integrated snow samples were collected using a Teflon core tube, on the lake surface just before snowmelt. Average canopy (foliage and stems) mercury pools were estimated by using a Leaf Area Index (LAI) map of the watershed derived from LiDAR, an LAI–biomass relationship (31), and mercury concentrations at 20 upland and 3 wetland sites in August 2003. Ground vegetation mercury pools were estimated from areal biomass and average mercury concentrations of ground vegetation at each of the same 23 sites. Mercury masses in upland soils in the basin were estimated from coring surveys with 2.5-cm diameter polycarbonate coring tubes. For mercury concentrations, cores were taken from 88 randomly distributed sites in October 2003 and were sectioned into two major horizons: organic horizon and bottom mineral horizon. Average depths and bulk densities for the upland soil horizons were determined by a larger survey using 185 sites aligned along 37 transects. These data were combined to calculate areal mercury masses for the whole soil depth. In the wetland, cores were taken from 16 sites and were sectioned in 4-cm intervals for measurement of ambient and spike mercury concentrations. Average bulk density was determined at 18 sites and was used with mercury concentrations to calculate areal masses for the upper 5 cm of peat. In the lake, intact sediment cores were collected by diver, sectioned within a few hours and immediately frozen. Cores were taken from 11 sites in the fall of 2003 at water depths of 0.2–11 m and were sectioned into 2-cm intervals. Mercury and bulk density were measured on the same sections and were used to calculate areal mercury mass for each site.

Mass flux of terrestrial isotopes to the lake was estimated from event and base-flow concentrations and estimates of terrestrial runoff. Volumetric flows were monitored continuously at four representative locations in the basin and were then scaled up to the full basin by using the U.S. Geological Survey's Precipitation-Runoff Modeling System (32).

Lake water samples were pumped through acid-washed Teflon tubing into acid-cleaned Teflon bottles by using the "clean hands–dirty hands" protocols (33). Zooplankton samples were taken and prepared for methylmercury analysis as described previously (34). *H. azteca* invertebrate samples were collected by kick-sampling and sweep-netting of epilimnetic sediments and prepared for analysis as described elsewhere (27). Yellow perch were collected using small-mesh gill nets (6–10 mm) set for short time periods (<15 min), and muscle samples were processed as described previously (27). All biota were frozen until analysis.

Analytical Methods. Total mercury (THg) in water was oxidized to inorganic Hg(II) by the addition of BrCl, reduced to Hg(0) using $SnCl_2$, purged onto gold traps, and analyzed after thermal desorption by inductively coupled plasma (ICP)/MS (35). For THg, fish tissue, soil, peat, and sediment samples were digested in HNO_3/H_2SO_4 and quantified by ICP/MS using either an on-line continuous flow cold vapor system (35, 36) or a system with preconcentration on gold traps (2600 total mercury analyzer; Tekran, Knoxville, TN) for vegetation and soils (35, 36). Many samples received aliquots of ^{201}Hg(II) as an internal standard. Methylmercury in freeze-dried zooplankton and zoobenthos was extracted with KOH/MeOH. The methylmercury in water, sediment, soil, and peat samples was collected by distillation or extraction (35, 36). Methylmercury from all samples was ethylated by additions of $NaBEt_4$, and the volatile mercury species were purged and trapped. Samples were thermally desorbed and separated by gas chromatography before quantification by ICP/MS (35). THg and methylmercury analyses by ICP/MS were performed in four project laboratories. Interlaboratory calibrations were done on various sample types (35, 36), artifact formation of methylmercury during analysis was assessed, and routine analyses of appropriate certified reference materials were performed to ensure comparability of results among laboratories.

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1. Lindberg S, Bullock R, Ebinghaus R, Engstrom D, Feng X, Fitzgerald W, Pirrone N, Prestbo E, Seigneur C (2007) *Ambio* 36:19–32.
2. Canadian Council of Ministers of the Environment (2000) *Canadian Environmental Quality Guidelines* (Canadian Council of Ministers of the Environment, Winnipeg, Canada).
3. U.S. Environmental Protection Agency (2005) 2004 National Listing of Fish Advisories (EPA Fact Sheet EPA-823-F-05-004). Available at www.epa.gov/waterscience/fish/advisories/2004/index.html. Accessed April 5, 2007.
4. Wiener JG, Krabbenhoft DP, Heinz GH, Scheuhammer AM (2003) in *Ecotoxicology of Mercury: Handbook of Ecotoxicology*, eds Hoffman DJ, Rattner BA, Burton GA, Jr, Cairns J, Jr, (CRC, Boca Raton, FL), 2nd Ed, pp 409–463.
5. Jiang G-B, Shi J-B, Feng X-B (2006) *Environ Sci Technol* 40:3672–3678.
6. Munthe J, Bodaly RA, Branfireun B, Driscoll CT, Gilmour C, Harris R, Horvat M, Lucotte M, Malm O (2007) *Ambio* 36:33–44.
7. Bodaly RA, Rudd JWM, Fudge RJP, Kelly CA (1993) *Can J Fish Aquat Sci* 50:980–987.
8. Gilmour CC, Henry EA (1991) *Environ Pollut* 71:131–169.
9. Hurley JP, Benoit JM, Babiarz CL, Shafer MM, Andren AW, Sullivan JR, Hammond R, Webb DA (1995) *Environ Sci Technol* 29:1867–1875.
10. Kelly CA, Rudd JWM, Bodaly RA, Roulet NP, St. Louis VL, Heyes A, Moore TR, Schiff S, Aravena R, Scott KJ, *et al.* (1997) *Environ Sci Technol* 31:1334–1344.
11. Kelly EN, Schindler DW, St. Louis VL, Donald DB, Vladicka KE (2006) *Proc Natl Acad Sci USA* 103:19380–19385.
12. St. Louis VL, Rudd JWM, Kelly CA, Barrie LA (1995) *Water Air Soil Pollut* 80:405–414.
13. Rudd JWM (1995) *Water Air Soil Pollut* 80:697–713.
14. St. Louis VL, Rudd JWM, Kelly CA, Beaty KG, Flett RJ, Roulet NT (1996) *Environ Sci Technol* 30:2719–2729.
15. St. Louis VL, Rudd JWM, Kelly CA, Hall BD, Rolfhus KR, Scott KJ, Lindberg SE, Dong W (2001) *Environ Sci Technol* 35:3089–3098.
16. Hintelmann H, Harris R, Heyes A, Hurley JP, Kelly CA, Krabbenhoft DP, Lindberg S, Rudd JWM, Scott KJ, St. Louis VL (2002) *Environ Sci Technol* 36:5034–5040.
17. Swain EB, Engstrom DE, Brigham ME, Henning TA, Brezonik PL (1992) *Science* 257:784–787.
18. Johansson KA, Aastrup M, Andersson A, Bringmark L, Iverfeldt A (1991) *Water Air Soil Pollut* 56:267–281.
19. Bloom NS (1992) *Can J Fish Aquat Sci* 49:1010–1017.
20. Eckley CS, Hintelmann H (2006) *Sci Total Environ* 368:111–125.
21. Branfireun BA, Krabbenhoft DP, Hintelmann H, Hunt R, Hurley JP, Rudd JWM (2005) *Water Resour Res* 41:W06016.
22. Blanchfield PJ, Paterson M, Podemski CL, Hintelmann H (2004) *RMZ Mater Geoenviron* 51:838–840.
23. Ramlal PS, Kelly CA, Rudd JWM, Furutani A (1993) *Can J Fish Aquat Sci* 50:972–979.
24. Rudd JWM, Turner MA, Furutani A, Swick A, Townsend BE. (1983) *Can J Fish Aquat Sci* 40:2206–2217.
25. Orihel DM, Paterson MJ, Gilmour CG, Bodaly RA, Blanchfield PJ, Hintelmann H, Harris RC, Rudd JWM (2006) *Environ Sci Technol* 40:5992–6000.
26. Orihel DM, Paterson MJ, Blanchfield PJ, Bodaly RA, Hintelmann H (2007) *Environ Sci Technol* 41:4952–4958.
27. Paterson MJ, Blanchfield PJ, Podemski C, Hintelmann HH, Gilmour CC, Harris R, Ogrinc N, Rudd JWM, Sandilands KA (2006) *Can J Fish Aquat Sci* 63:2213–2224.
28. Brunskill GJ, Schindler DW (1971) *J Fish Res Board Can* 28:139–155.
29. Sandilands KA, Rudd JWM, Kelly CA, Hintelmann H, Gilmour CC, Tate MT (2005) *Can Tech Rep Fish Aquat Sci* 2597:viii + 48 p.
30. Hall BD, Manolopoulos H, Hurley JP, Schauer JJ, St. Louis VL, Kenski D, Graydon J, Babiarz CL, Cleckner LB, Keeler GJ (2005) *Atmos Environ* 39:7557–7569.
31. Gower ST, Vogel JG, Norman JM, Kucharik CJ, Steele SJ, Stow TK (1997) *J Geophys Res* 102:29029–29041.
32. Leavesley GH, Lichty RW, Troutman BM, Saindon LG (1983) *Precipitation-Runoff Modeling System: User's Manual*, US Geological Survey Water-Resources Investigations Report 83-4238 (US Geological Survey, Reston, VA), p 207.
33. Olson ML, DeWild JF (1999) in *Contamination of Hydrologic Systems and Related Ecosystems*, US Geological Survey Report WRIR 99-4018B, eds Morganwalp DW, Buxton HT (US Geological Survey, Reston, VA), pp 191–200.
34. Paterson MJ, Rudd JWM, St. Louis VL (1998) *Environ Sci Technol* 32:3868–3874.
35. Hintelmann H, Ogrinc N (2003) in *Biogeochemistry of Environmentally Important Trace Elements*, eds Cai Y, Braids CO (Am Chem Soc, Washington, DC), Vol 835, pp 321–338.
36. DeWild JF, Olund SD, Olson MK, Tate MT (2004) in *Techniques and Methods Book 5 A-7* (US Geological Survey, Reston, VA), p 13.
37. Southworth G, Lindberg S, Hintelmann H, Amyot M, Poulain A, Bogle M, Peterson M, Rudd J, Harris R, Sandilands K, *et al.* (2007) *Environ Toxicol Chem* 26:53–60.

Indicator Synthesis:

Selection Rationale, Modelling Results and Monitoring Considerations for Key Indicators of the Terrestrial Ecoysystem Management Framework

Prepared for: Sustainable Ecosystem Working Group of the Cumulative Environmental Management Association

Prepared by: Barry Wilson and Dr. Brad Stelfox

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Silvatech Group

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1. Rationale for the Selection of Categories, Goals and Indicators

In January 2006, through a consensus based decision-making process, the Sustainable Ecosystems Working Group (SEWG) of the Cumulative Environmental Management Association (CEMA) adopted a set of selection criteria to determine the ability of each candidate indicator to inform the decisions leading to the development of the Terrestrial Ecosystem Management Framework (TEMF). SEWG's Goals and Indicators are categorized into three broad groups; Environmental, Economic and Resource Use.

The Environmental indicators were chosen based on relevance, response variability, management relevance, feasibility and utility as shown in the table below:

Ecological relevance	• Ecological importance, linked to structure or function • Applicable to multiple scales of ecological organization
Response variability	• Predictable response to stressors, known power • Anticipatory, sensitive, early warning • Low natural variability, high signal : noise
Management relevance	• Stated in SRD, SEWG, CEMA management goals etc. • Applicable to management decisions • Important to stakeholders for food, recreation, sustenance
Feasibility of implementation	• Not cost-prohibitive to measure • Low impact of measurement • Easy to measure, repeatable
Interpretation and utility	• Stress response distinguishable from natural variability • Can help to identify causes of ecological response • Historic data, baseline conditions known

Table 1: Environmental Indicator Criteria Details

The Economic indicators were considered for inclusion based on economic and management relevance management relevance, simplicity, validity, affordability of data and aggregability. The Resource Use (originally Social Cultural) indicators were considered for inclusion based on social and cultural management relevance, simplicity, validity, affordability of data and aggregability

1.1. Ratified Goals and Indicators

Following the selection of indicators, a crosscheck with the Goals was undertaken, some revisions were made, and SEWG ratified 12 Goals and 21 Indicators.

Category	Goal	Indicator
Environmental	Sustain viable and healthy populations of wildlife and fish.	Index of Native Fish Integrity
		Woodland Caribou habitat and population response
		Moose habitat and population response
		Fisher habitat
		Old Growth Forest Birds habitat
		Black Bear habitat and population response
	Sustain the natural range of vegetation communities, successional patterns and ecological processes.	Area, Pattern and Age of Vegetation types
	Preserve the diversity of species, ecosystems and landscapes	Area, Pattern and Age of Vegetation Types
		Percent Area Under Protected, Intensive & Extensive Status
	Sustain natural watersheds and their elements	Water Flow Dynamics (Discontinuity of Non-mainstem river systems)
		Density of linear features
Economic	Sustain a land base for timber harvest	Area of productive forest land and percentage of growing stock
	Maintain opportunities for oil sands and hydrocarbon reserves development	Bitumen production m3 (including coke and asphaltines)
		Conventional oil production m3 (light and heavy)
		Natural gas and condensates production m3
	Maintain opportunities for Aggregate resource development	Aggregate production including limestone (tonnes)
	Maintain opportunities for mineral resource development	Mineral (non-hydrocarbon) production including uranium (tonnes)
	Maintain opportunities for tourism development	# of visitors
Resource Use	Maintain opportunities for traditional Aboriginal land use	Index of Native Fish Integrity
		Woodland Caribou habitat and population response
		Moose habitat and population response
		Fisher habitat
		Black Bear habitat and population response
		Area, Pattern and Age of Vegetation types
	Sustain recreational capability and availability of wilderness opportunities	# of ha by recreational reserve type (including *high capability*)
		# of ha of reservation or disposition by recreation type
		Density of linear features
	Maintain opportunities for consumptive, non-commercial use of fish, wildlife and plants.	recreational hunting harvest level for moose
		recreational hunting harvest level for black bear

Table 2: Ratified Goals and Indicators

1.2. Non-Ratified Indicators That Were Considered

The following indicators were considered but determined not to be directly included in the modelling work. These indicators may warrant consideration at a later date.

Canadian Toad – research is being done. Currently being addressed at operational scale with pre-disturbance assessments.

Beaver - importance is recognized but information is not readily available. Further work is required as does have impacts on infrastructure. See work by L. Foote.

Gray Wolf - tracks same phenomena as Moose.

Artic Grayling - considered in Index of Native Fish Integrity (INFI).

River Otter - Consider future inclusion in same manner as Beaver and Muskrat.

Lake Trout - considered in INFI.

Ecologically significant and unique natural landform features - covered by area, pattern and age of vegetation types and percent area Protected, Intensive and Extensive Status

Wetlands and Uplands – covered by area, pattern and age of vegetation types.

Riparian Habitat - covered by area, pattern and age of vegetation types.

CHR sites – some data is available through fish and wildlife but not comprehensive so require more information.

Walleye - considered in INFI.

Northern Pike- considered in INFI.

Ducks and Geese - reflected adequately in environmental indicators.

Bald Eagle - Consider monitoring and/or Traditional Ecological Knowledge (TEK) in as primary predator species.

Common Loon - Consider monitoring and/or TEK. Also flag Swans.

Muskrat - Consider inclusion in same manner as Beaver and River Otter.

Lake Whitefish - considered in INFI.

Burbot - considered in INFI.

Mixed Wood Forest Birds - covered by proxy by area, pattern and age of vegetation

Mushrooms, Berries, etc. - covered by proxy by area, pattern and age of vegetation and Goal "Maintain opportunities for traditional Aboriginal land use"

Type & Area of Vegetation Communities - Merged into "Area Pattern and Age of Vegetation Types"

Distribution & Pattern of Vegetation Communities - Merged into "Area Pattern and Age of Vegetation Types"

Amount and Pattern of Old Growth - Merged into "Area Pattern and Age of Vegetation Types"

Types, Area, Patch Size and Distribution of unique vegetation communities and age classes of concern - Merged into "Area Pattern and Age of Vegetation Types"

Area of soil Disturbance - covered by percent area Protected, Intensive and Extensive Status

Duration of time soil is non-vegetated - covered by proxy by area, pattern and age of vegetation

Number and diversity of soil types - covered by proxy by area, pattern and age of vegetation

Protect ecologically significant or unique landform features - covered by percent area Protected, Intensive and Extensive Status

Sustain natural watersheds and their elements including riparian habitat - Merged into "Area Pattern and Age of Vegetation Types"

Ratio of wetlands to uplands in each river basin of order x or higher - covered by proxy by area, pattern and age of vegetation and Watershed Discontinuity

Ensure availability of Wilderness Experience - covered by percent area Protected, Intensive and Extensive Status and #of ha by recreational reserve type.

Percent of key viewsheds important recreational capability - covered by percent area Protected, Intensive and Extensive Status and #of ha by recreational reserve type.

Km of access in each natural subregion - covered by Density of Linear Features.

# of wildland Areas protected in each natural subregion - covered by percent area Protected, Intensive and Extensive Status

# of fromalized backcountry campistes - covered by percent area Protected, Intensive and Extensive Status and #of ha by recreational reserve type.

Km trail/ km2 - covered by Density of Linear Features.

Accessibility of Extensive Recreational Sites - covered by percent area Protected, Intensive and Extensive Status and #of ha by recreational reserve type and Density of Linear Features.

Lynx/hare - tracks same phenomena as Gray Wolf – high correlation with Moose. Subsistence and cultural keystone species for Aboriginal peoples - recognition for traditional Aboriginal covered under Goal “Maintain opportunities for traditional Aboriginal land use”

Pileated Woodpecker - partially covered by old growth forest birds - too fine a scale.

Populations of Provincial and Federally listed species - The TEMF is strategic and is not designed to address species at risk.

Natural Landform features - highly subjective.

Number, type and location of ecologically significant features - covered by percent area Protected, Intensive and Extensive Status and #of ha by recreational reserve type.

Sustain Aesthetic Values - covered by percent area Protected, Intensive and Extensive Status and #of ha by recreational reserve type.

2. Monitoring Indicator Performance

The monitoring system is intended to provide feedback to decision makers and managers on the effectiveness of their management strategies and approaches as well as to provide a basis for refinements and improvements in future modelling and the TEMF.

2.1. The System

Following are a series of tasks or steps outlining a monitoring system designed to objectively guide adaptive management activities including changes to industrial development, legislation or policy, public values and to accommodate standard certification procedures. The steps identified here are assumed to start with the adoption of the TEMF by the Alberta Government (GoA).

2.1.1. Management Objectives Confirmed

Montioring will be used to measure indicator performance as management strategies are implemented.

2.1.2. Monitoring & Data Collection

This is the actual monitoring of indicator and TEMF performance. Current inventory information about the landscape was used to establish current indicator status. Effective monitoring will require updating and/or acquiring new inventories, response algorithms and associated datasets. Figure 1 shows the breakdown of recommended monitoring tasks.

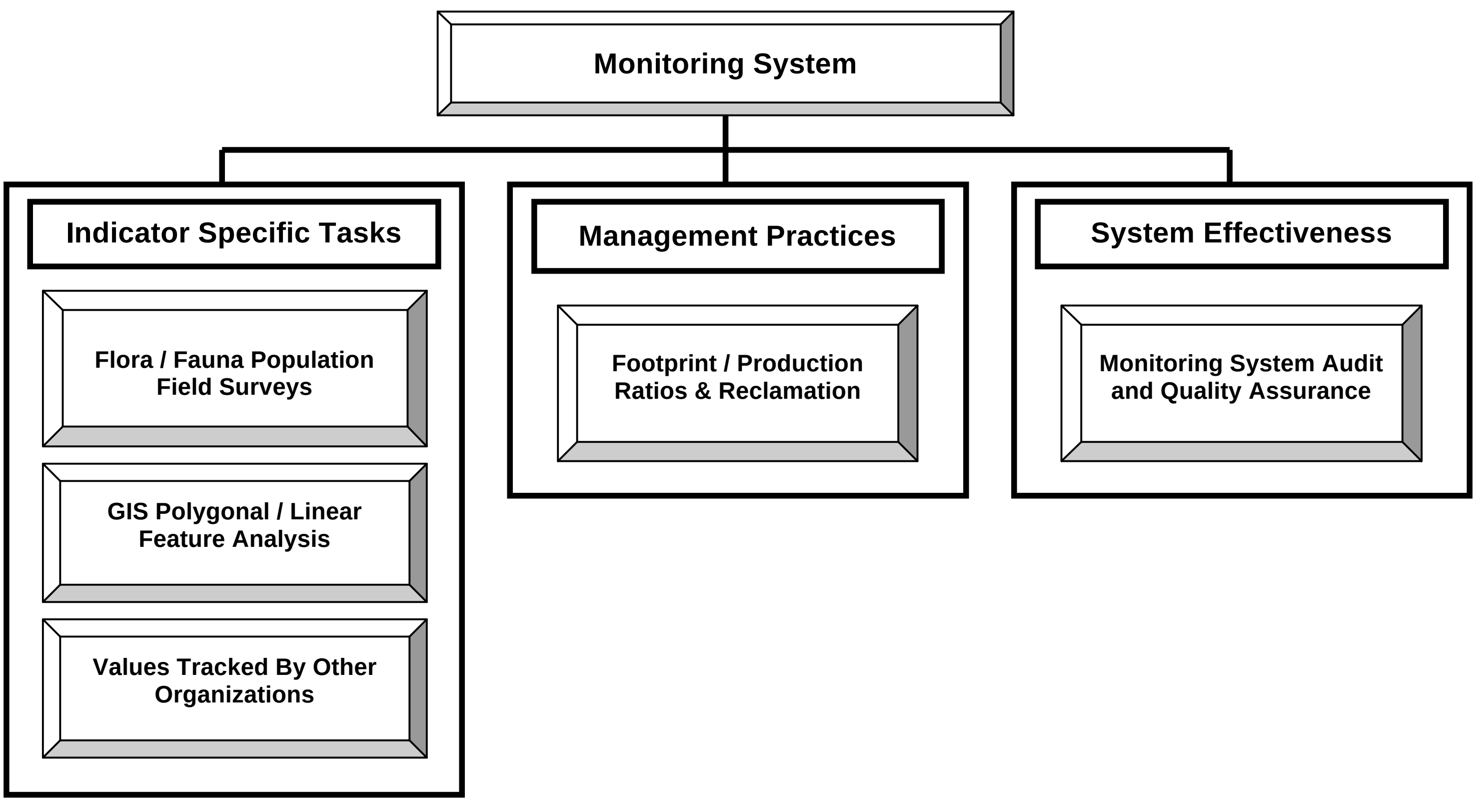

Figure 1: Description of Monitoring Tasks

The monitoring system is composed of 3 task categories: indicator specific, footprint metrics/trajectories and system effectiveness. This monitoring system is intended to be reflective of the integrated effects of numerous kinds of human-related stresses on identified values and also provides opportunities for refining our understanding of the particular causes of the effects. The system should be considered dynamic and is designed to be able to adapt to new findings or information and to this end, priorities identified in an information gap analysis along with new information and/or inventories that become available are collected and aggregated. This is a multi-step interactive process occurring over several years. There is a considerable amount of effort already invested in monitoring within the region and this system attempts to build upon those values to the greatest extent possible to maximize efficiency. Specific details on the precise roles and responsibilities of implementing a TEMF monitoring system are not determined. This is identified as an item requiring further development. The proposed monitoring system is composed of 5 main components as outlined below:

2.1.2.1. Field Surveys for wildlife populations and vegetation

The Alberta Biodiversity Monitoring Institute (ABMI) sampling grid should be used as the basis for building this sampling network. Sampling resolution is expected to be adequate for many of the TEMF indicators. Ground verified vegetation abundance could be utilized to validate remote sensed inventories.

2.1.2.2. GIS Polygonal and Linear Feature Analysis

The assessment and reporting of baseline conditions for polygonal inventories such as forest cover and linear feature inventories including roads, pipelines and seismic lines. Periodically re-assess conditions and compare changes over time noting changes differentiating between anthropogenic and natural disturbance as well as changes detected as a result of new inventory acquisition.

2.1.2.3. Other Agency Captured Information

The periodic reporting on data already collected by other organizations. This includes natural biotic data collected by agencies such as the Alberta Biodiversity Monitoring Insitute (ABMI) but also consumptive use data such as hydrocarbon, mineral and aggregate production, tourism visits, area of recreational reserve types and dispositions and recreational hunting harvest.

2.1.2.4. Models and Assumptions

The validation of TEMF assumptions including metrics of resource extraction rates and associated footprint, natural disturbances, management actions implemented and associated indicator response.   Where there are significant changes, re-evaluate spatial and temporal risk that may be associated with the changes.

2.1.2.5. Framework Effectiveness

Conducting periodic audits of TEMF effectiveness to guide adjustments, additions, deletions or modifications to the TEMF as appropriate. This will be a key component of adaptive management and provide a structured, iterative process to reduce uncertainty over time and maintain the TEMF as an effective cumulative effects management tool. The actual details of the system audit will need to be determined as part of initial TEMF implementation but ultimately is expected to be consistent with standardized certification management system audits enabling the TEMF to be certification eligible. For example, the

International Organization for Standardization provides requirements and guidance on good management practice including ISO 9001:2000 for Quality management and ISO 14001:2004 for Environmental management.

2.1.3. Analyze and Evaluate Data

At roughly a mid-point in the adaptive management loop (2 to 3 years), monitoring data is compiled, analyzed and summarized relative to initial expectations and an assessment of assumptions versus realized outcomes is made. Where there are variances from initial assumptions and expectations, it will be important to distinguish the observed effects relative to the agent of change such as baseline information, management assumptions, indicator response algorithms, market adjustments, regulatory requirements, technology improvements, etc. An assessment of the risk and uncertainty these changes introduce into the TEMF should be made both in magnitude and timing.

2.1.4. Update Data and Assumptions

In a format consistent with the current process, a stakeholder review of the monitoring results and available models and tools will be undertaken. This is also an opportune time to solicit public input regarding management expectations, priorities, concerns and suggestions. Stakeholders identify any revisions to data and assumptions to be made in preparation for supplementary scenario planning or options assessment deemed necessary in order to update the Management Framework.

2.1.5. Scenario Planning

With the advent of new and improved information, the identification of refined management approaches including new technologies and approaches to resource development, scenario planning can be effectively used to provide insight and understanding for TEMF refinement.

Overall, this approach is intended to objectively guide adaptive management activities including continuous improvement initiatives, legislative or policy change, public communication and to accommodate standard certification procedures.

3. Linking Indicator Performance Monitoring To Action

The TEMF monitoring approach is designed to objectively guide other stages in the adaptive management cycle including continuous improvement initiatives, legislative or policy change, public communication and to accommodate standard certification procedures. To that end, three categories of indicator monitoring are identified:

3.1. Management Objectives

The TEMF identifies measurable objectives for specific indicators at the Regional scale. These indicators include native fish, old growth forest birds, moose, fisher, black bears, old growth forest and the proportion of the region’s area in each of the triad zones. A gradient system identifies thresholds that trigger management responses ranging from further investigation to immediate remedial action.

3.2. Trends

The TEMF identifies indicators for which management response thresholds are not formulated but which will inform decisions on management strategies and approaches. These indicators include area, pattern and age of vegetation types, discontinuity of non-mainstem river systems, linear feature density, area of productive forest land, merchantable timber growing stock, bitumen, conventional oil, natural gas, mineral and aggregate production, population and visitor days, designated recreational areas and recreational hunting harvest. Other environmental, economic and social indicators monitored independent of the TEMF may also be appropriate to integrate into the framework in the future.

3.3. Benchmarking

A critical component of the TEMF is the establishment of a Protected Zone that will, among other valuable contributions, serve as the benchmark or control measure of natural processes and associated indicator performance. Sub-regional monitoring within this zone serves two very important functions. First, it will assist in the refinement and definition of the NRV against which regional level indicator performance will be measured. Secondly, it will assist with distinguishing between change that is brought about by development within the region and change that is beyond the management control of the TEMF. This is of particular importance in view of changing landscape or global variables that could alter current ecosystem composition and function. For example, climate change has the potential to bring about significant change in regional ecosystem structure that is not a direct result of anthropogenic footprint within the region and it will be important to understand the difference.

4. Alberta Biodiversity Monitoring Institute Integration

When fully operational, the ABMI will provide information on the state of Alberta's biodiversity. The ABMI employs a cumulative-effects monitoring approach that is targeted at detecting the ecological effects of a diverse set of environmental stresses on broad suites of indicators (Manley et al. 2004). As such, the ABMI assesses the performance toward management objectives such as "regional sustainability" or "ecological integrity" (Mulder et al. 1999). The ABMI monitors biodiversity by sampling 1656 permanent sites distributed evenly across Alberta. Each survey site consists of a terrestrial survey site that is surveyed once every 5 years. Terrestrial survey sites are established on a 20 km systematic grid with a random distance and directional offset of up to 4 km from the 20 km systematic grid. Terrestrial survey sites are not stratified and, therefore, environmental conditions are sampled in proportion to their availability on the landscape. For example, biodiversity monitoring sites exist in cities, public and private lands, industrial installations, protected areas, and lakes.[1] Detailed information regarding the ABMI can be found online at www.abmi.ca

There is potential for a high degree of synergy between the TEMF and ABMI. These two complementary programs can harmonize numerous activities including: common data collection protocols, common data collection activities, and consistent methodologies for analyzing and aggregating information.[2] The ABMI has good potential to contribute to data collection and reporting on one-half of the SEWG ratified environmental and resource use indicators as follows:

High integration: moose habitat and population response, fisher habitat, old growth forest birds habitat, area/pattern/age of vegetation types, density of linear features, stream crossings per km of streams and rivers and area of productive forest land/percentage of growing stock.

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[1] www.abmi.ca

[2] Addressing SEWG Ratified Indicators Using the ABMP, November 2006

Moderate integration: index of native fish integrity, woodland caribou habitat and population response, black bear habitat and population response and regional percent intensive (which could be used to derive extensive knowing the area protected).

Natural Range of Variation (NRV) is recommended as a reference for indicator performance within the TEMF. Modelling has established a first estimate of NRV for Management Objective indicators with the exception of moose and black bear populations. This will need to be refined and the ABMI can contribute to this refinement. The ABMI will describe the relationship for either occurrence or abundance of an individual species to varying levels of human disturbance and use this information to estimate reference conditions (NRV) in the absence of human activity. In order to account for natural variation an NRV using the 20th and 80th percentiles of sample data will be determined.

The ABMI sampling design is expected to enable most indicators to be reported at a scale of approximately 1 million hectares, roughly 15% of the RMWB. This monitoring resolution is expected to be well within the level necessary to meet the management objective, trend and benchmarking indicator requirements identified in the TEMF – with the possible exception of moose, black bear and individual caribou herd populations. As such, the ABMI is an excellent fit to directly support regional management within the TEMF. It would be helpful to synchronize ABMI data capture appropriately with the Monitoring and Data Capture phase of the TEMF monitoring strategy in order to facilitate cost-effective and timely collection and interpretation of data.   To achieve maximum value and integration, it is recommended that the GoA engage with the ABMI to ensure that program data collection protocols, products and services meet TEMF requirements.

The ABMI uses Information Pyramids as the framework for aggregating and simplifying ecological knowledge. Conceptually, Information Pyramids are appealing because they support integration of diverse forms of biotic and abiotic data into synthesized, transparent and understandable messages. Pyramids have high intuitive appeal to both ecologists and decision-makers because they make it easy to communicate and understand the type of data available, how it is organized, and how it is being combined. The figures below shows the ABMI Species Pyramid and Habitat Pyramid.

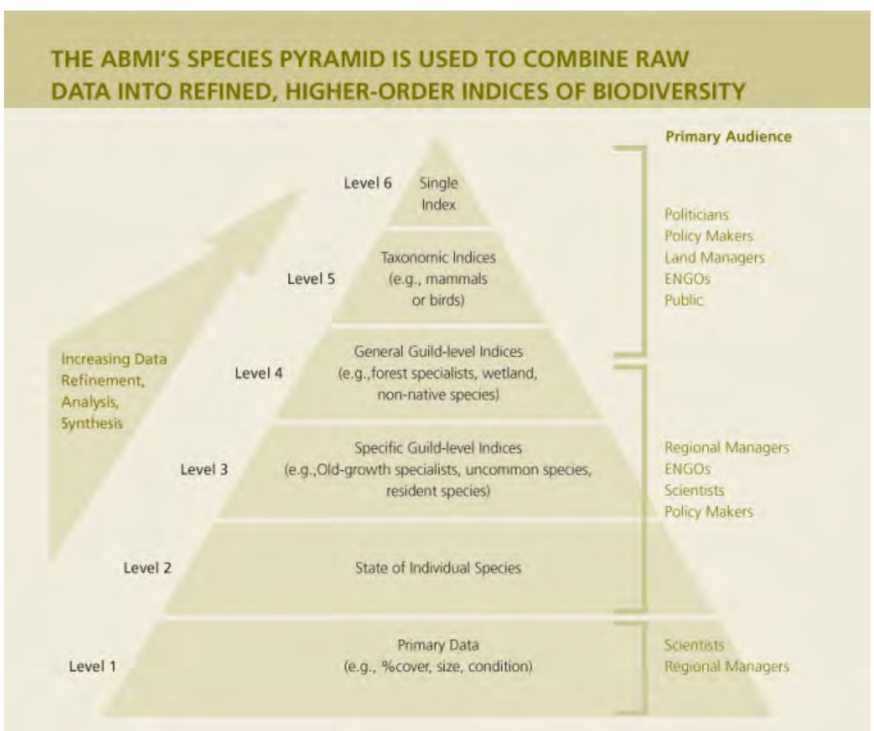

Figure 2: ABMI Species Pyramid

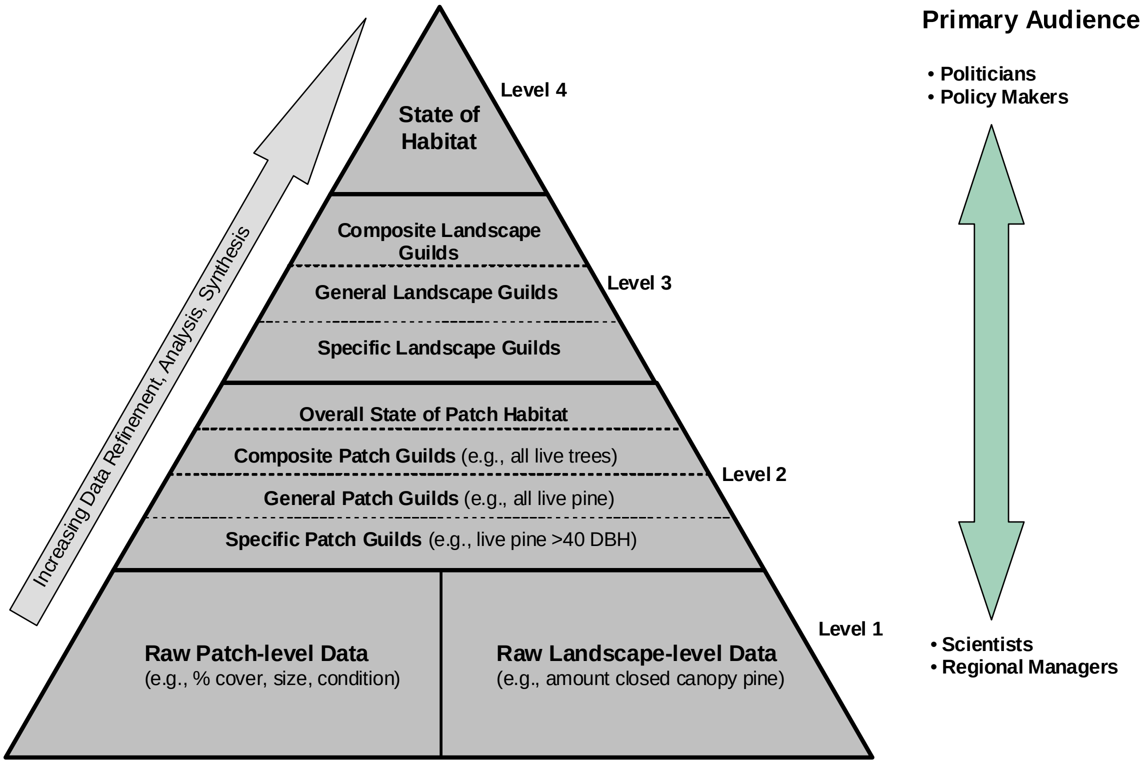

Figure 3: ABMI Habitat Pyramid

5. Management Objective Indicators That Can Trigger a Management Response

5.1. Indicator: Index of Native Fish Integrity (INFI)

5.1.1. Indicator Category: Environmental / Resource Use

5.1.2. Goal: Sustain viable and healthy populations of wildlife and fish

5.1.3. Modeled Condition - Red

Indicator is currently more than 20% below lower limit of NRV and requires immediate management intervention.

5.1.4. Indicator Rationale:

INFI is one of the environmental indicators chosen by SEWG for this project through workshops utilizing agreed upon selection criteria. Consideration was given to developing population models for walleye and northern pike and to include these as the indicators representative of the fish resource. However, an overall approach focused on native fish as a guild was determined to be more appropriate for this strategic level study. The index algorithm was developed through a delphi workshop composed of the following experts:

Mike Sullivan - Alberta Fish and Wildlife Division, Sustainable Resource Development

Alastair Franke - Alberta Conservation Association

Paul MacMahon - Alberta Fish and Wildlife Division, Sustainable Resource Development

Brian Makowecki – Department of Fisheries and Oceans, Canada

Andrew Paul - Alberta Fish and Wildlife Div., Sustainable Resource Development

Larry Rhude - Fish and Wildlife Division, Sustainable Resource Development

Mark Spafford – Alberta Pacific Forest Industries Ltd.

Terry Van Meer – Syncrude Canada Ltd.

Brad Stelfox - Forem Technologies

5.1.5. Indicator Natural Range of Variability:

The NRV was determined from 50 stochastic ALCES runs using a back-casted dataset. An index value of 1 represents the perfect combination of habitat and population to represent maximum native fish integrity. An index value of 0 would represent no native fish populations or habitat present. The natural range acknowledges that conditions are not always ideal and that the index could be expected to fluctuate naturally between 0.81 and 0.99

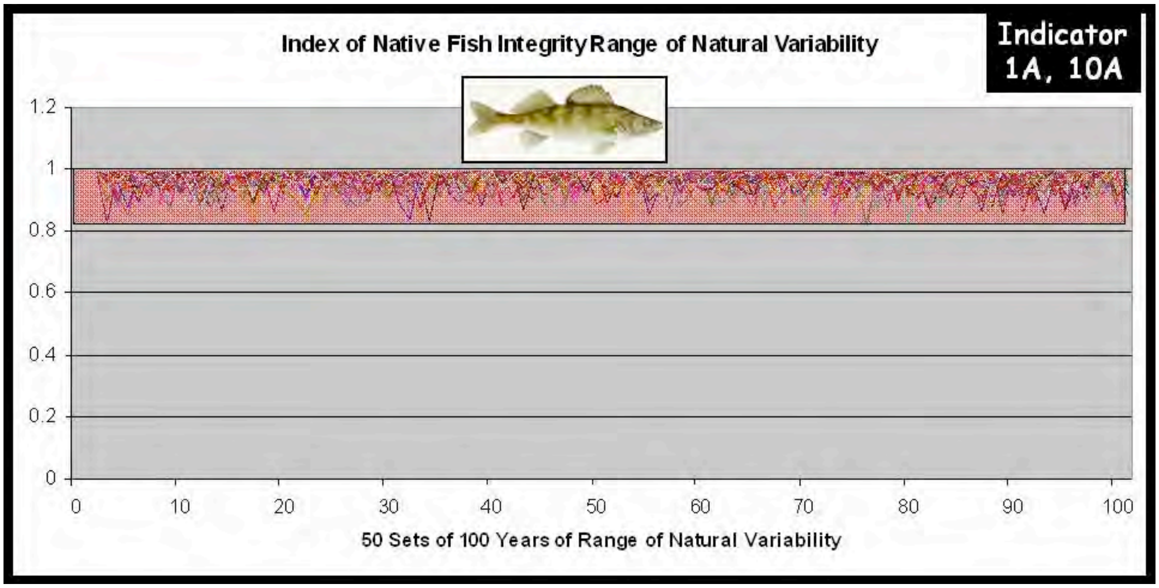

Figure 4: Index of Native Finsh Integrity Natural Range of Variability

5.1.6. Forecasted Scenario Outcomes for Index of Native Fish Integrity:

The graph below shows the forecasted indicator performance using the ALCES sub-model of the Index of Native Fish Integrity with the NRV as a reference point. Scenarios forecast include the Base Case, Innovative Approaches, Protected Area and Access Management.

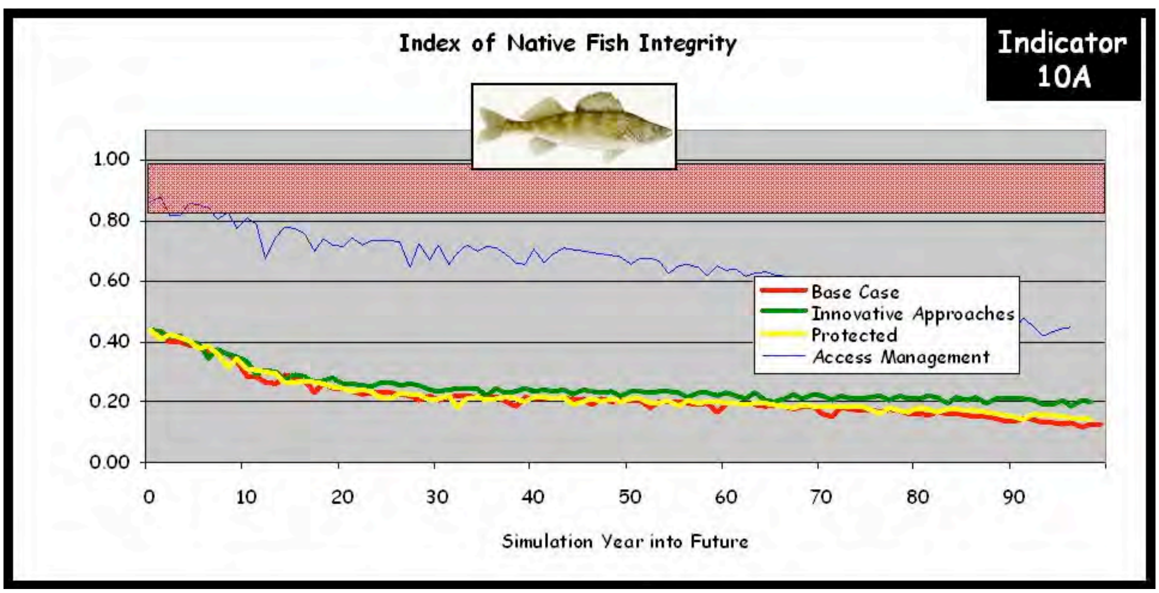

Figure 5: Forecasted INFI performance in Main Program Modelling

Currently, the index is forecast to be approximately 50% below lower limit of NRV because of historical human activity levels including a significant increase in watershed discontinuity associated with linear features.

As development in the region continues, access management is identified as the management strategy having the most significant opportunity to mitigate future effects. In the absence of access management, the model suggests that the INFI could drop a further 25% below the NRV. Access management could mitigate the effects of future human acitivity and linear features by roughly 50%.

5.1.7. Sensitivity Analyses

Indicator performance was forecast at double bitumen production rates, double the reclamation time and both double bitumen production and double reclamation time to test the risk associated with these key modelling uncertainties.

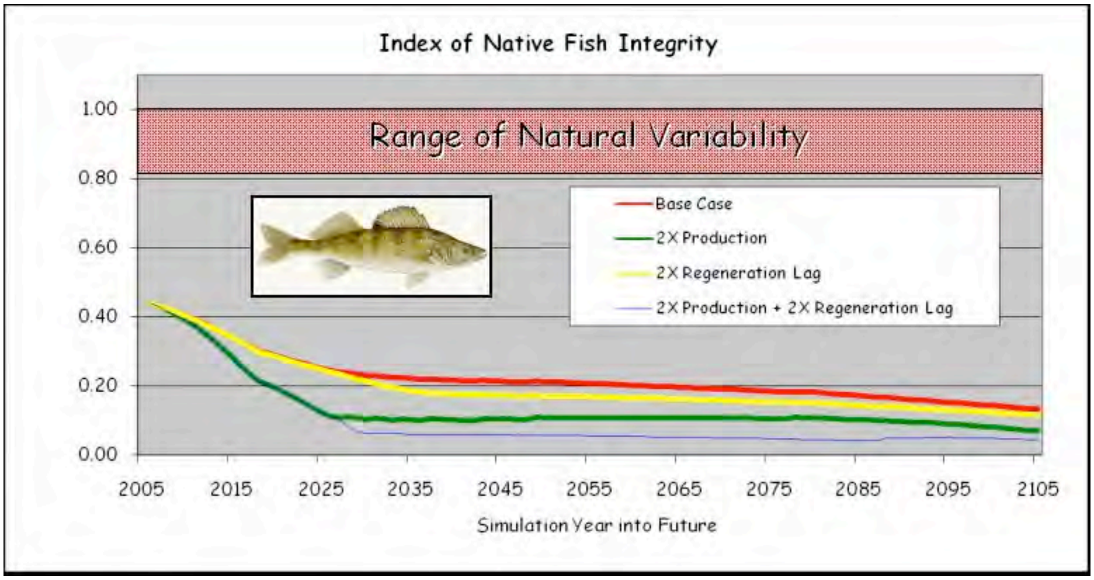

Figure 6: Forecasted INFI performance in Sensitivity Modelling

The indicator performance is sensitive to all three uncertainty scenarios tested and is most sensitive to a double production and double reclamation lag. Risks are greatest associated with the doubling of production assumptions. When double reclamation lag is combined with double bitumen production rates, forecasted indicator performance falls to approximately 93% below the lower limit of NRV within 25 years. The risk is elevated further owing to the temporal nature of the effect and that the effects would be felt in the near term.

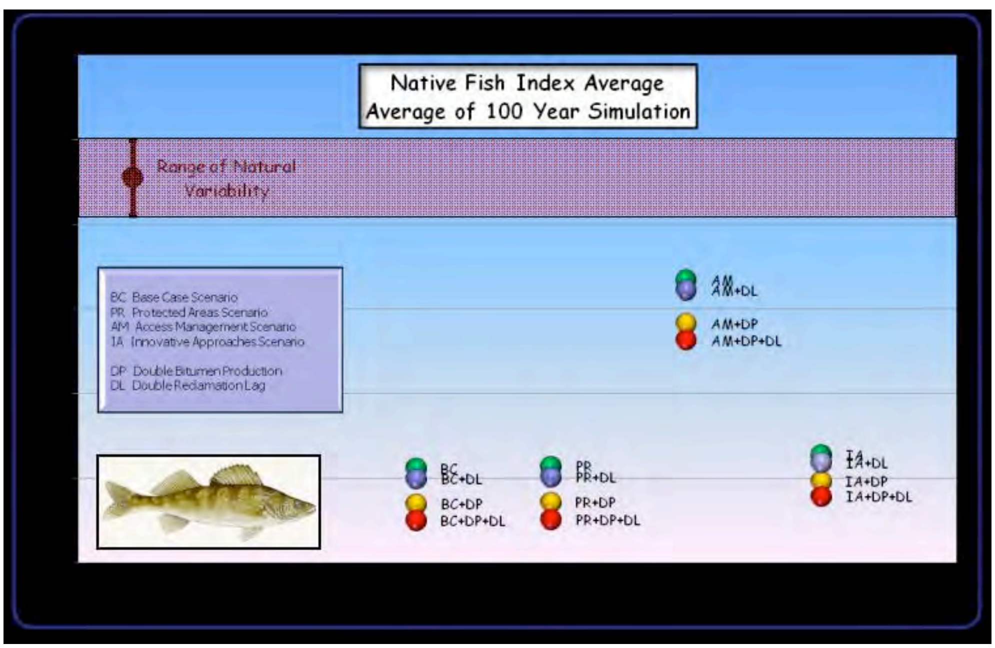

Figure 7: Comparison of Management Strategy effect on the average of INFI forecasted performance over the 100 year planning horizon

The potential for access management to mitigate effects is demonstrated in the sensitivity analyses similar to the scenario forecasting. Overall, however, no scenario tested is able to fully recover the INFI to within NRV within the forecast period.

5.1.8. Key Indicator Performance Drivers:

- Very sensitive to human activity levels such as angling
- Sensitive to the prescence of linear features, hanging culverts and watershed discontinuity
- INFI performance within the Protected Zone is directly linked to activities in the extensive and intensive zones because watercourses cross Triad zones. As a consequence, angling pressure and activities causing watershed discontinuity outside the Protected Zone will have significant impacts on INFI within the Protected Zone.

5.1.9. Indicator Specific Monitoring Considerations

The INFI function developed for the TEMF requires 4 variable inputs as described below:

5.1.9.1. GIS Polygonal and Linear Feature Analysis

Linear Edge (km/km^2) and Watershed Discontinuity (crossings/km rivers and streams)

5.1.9.2. Government Agency Captured Information

Human density (# $people/km^2$) and Water Use (m^3/yr)

5.1.9.3. Level of Integration from ABMI: Moderate

The ABMI can contribute to data collection for reporting on INFI performance at the regional scale by reporting on linear edge density and watercourse crossing density. In addition, ABMI protocols are consistent with ASRD protocols and therefore future collaborations are expected to contribute to finer resolution evaluations.

http://www.abmi.ca/abmi/reports/reports.jsp?categoryId=0

5.1.10. Other Identified Organizations

5.1.10.1. Agency: Alberta Fish and Wildlife

Activities: AFW manages fish as a game species, selling licences and setting quotas for fishing based on trend information.

http://www.srd.gov.ab.ca/fishwildlife/fishingalberta/default.aspx

5.1.10.2. Agency: Department of Fisheries and Oceans

Activities: The Department is committed to ensuring safe, healthy, productive waters and aquatic ecosystems, for the benefit of present and future generations. It advances these goals by maintaining the highest possible standards of sustainable development, environmental stewardship and public safety.

http://www.dfo-mpo.gc.ca/home-accueil_e.htm

5.1.11. Identified scientific knowledge gaps:

- NRV Definition
- Linking fish integrity to Inflow Needs
- Quantifying the effectiveness of Access Management

5.2. Indicator : Woodland Caribou habitat and population response

5.2.1. Indicator Category: Environmental

***Goal*:** Sustain viable and healthy populations of wildlife and fish

5.2.2. Modeled Condition - Red

The TEMF has coded woodland caribou habitat and population response as red, based on existing monitoring data. Model simulations suggest a consistent decline in regional population over the entire forecast period that would eventually lead to extirpation without management intervention. Both modelled and monitoring data provide supportive evidence that regional caribou populations will be severely challenged if management intervention does not occur.

It is important for readers to understand that the 10% reduction value from NRV (Table 2, Management Response Triggers, TEMF) does not apply well to caribou as that logic is largely based on habitat performance, whereas the ACC equation for caribou reflects population level response. For example, a lambda value of 0.93 for several consecutive years could result in local extirpations of herds but not violate the 10% rule.

5.2.3. Indicator Rationale:

Woodland Caribou is one of the environmental indicators chosen by SEWG for this project through workshops utilizing agreed upon selection criteria. Woodland caribou are an important biotic component of boreal forest systems and play a key role in predator/prey and herbivory dynamics. Aboriginal peoples have used caribou for subsistence hunting, and First Nation cultures and traditions are often bonded with caribou ecology. Since caribou are found in low densities, are slow to reproduce, and are sensitive to increased predator mortality tied to landscape modifications, they can serve as an important indicators of human impacts on boreal ecosystems (Source: Alberta Caribou Committee).

The fact that Woodland Caribou has been identified as a species at risk by the Governments of Alberta and Canada, its social importance, and the availability of strategic-level modelling functions considered appropriate for use in Alberta, were among the primary reasons for selection of boreal caribou as an environmental and resource use indicator.

5.2.4. Indicator Natural Range of Variability:

The ACC lambda equation formulated for use in ALCES was used:

(-.258*(Total_%_of_ZOI_of_Range)) - (.212*Fire\Insect_origin%_less_than_50_yrs) +1.14

ZOI = Zone of Influence and represents all FT and their buffers within caribou range. This value is expressed as a decimal percent of the total caribou range.

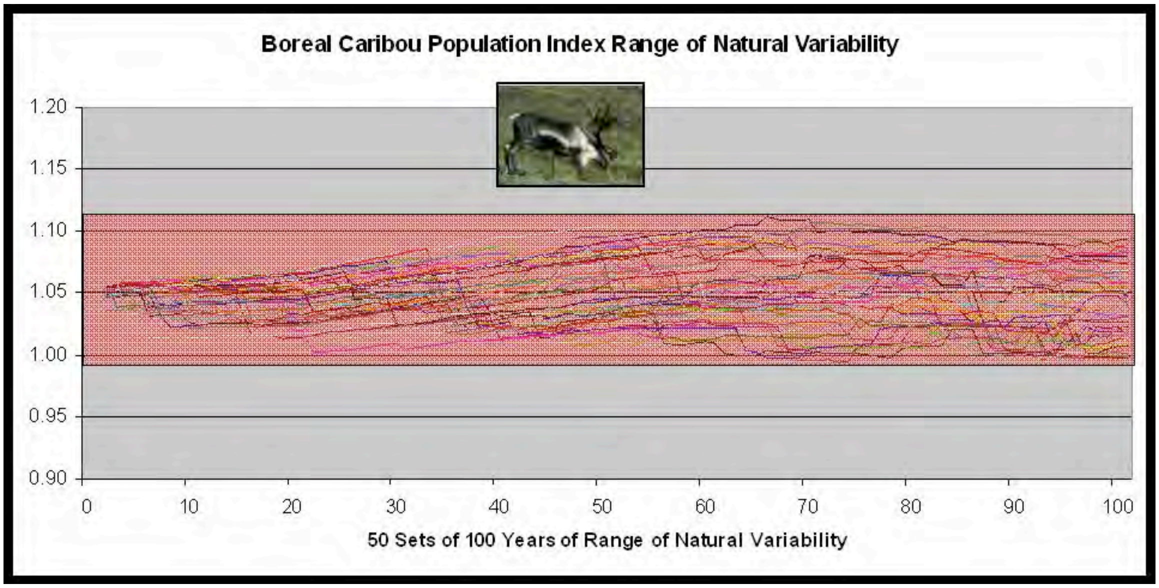

Figure 8: Woodland Caribou Population Natural Range of Variability

The NRV for boreal caribou lambda values was determined by conducting fifty 100-year stochastic simulations in ALCES run on the pre-industrial landscape driven by natural disturbance regimes. An lambda value of <1 means populations are declining; conversely, an index of >1 means populations are increasing. An index value of 1 would represent a stable population with no net increase or decrease. The natural range acknowledges that conditions are variable and that the index could be expected to fluctuate naturally between 0.97 and 1.10. Temporal variation in NRV is caused by changes in forest age and structure linked to episodic fire events.

5.2.5. Forecasted Scenario Outcomes for Woodland Caribou:

The graph below shows the forecasted indicator performance using the ACC/ALCES lambda function with the NRV as a reference point. Scenarios forecast include the Base Case, Innovative Approaches, Protected Areas, and Access Management.

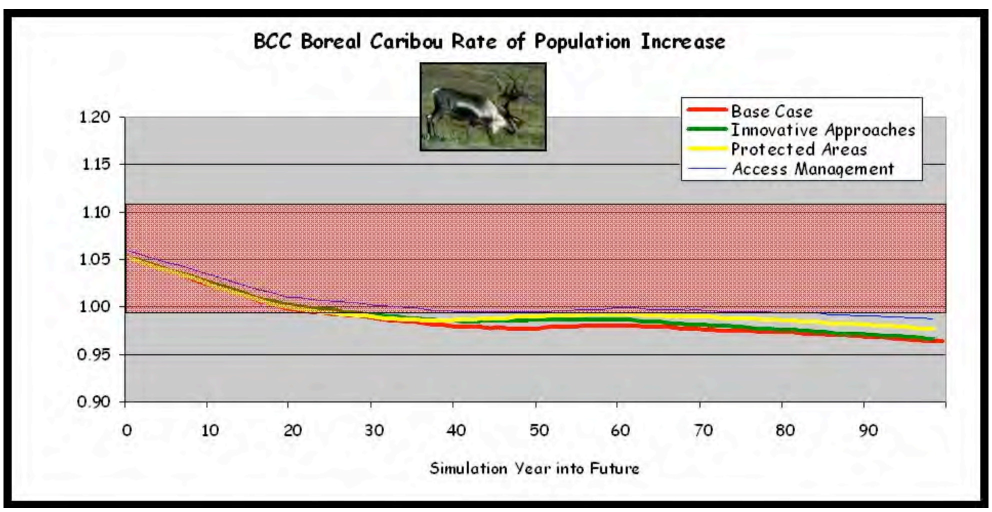

Figure 9: Forecasted Woodland Caribou Population performance in Main Program Modelling

Currently, the index is forecast to be within the NRV primarily due to relatively low historical human disturbance at the regional scale. Because the index is area-weighted across all caribou habitat, the current lambda values does not mean that all current subregions are favourable to caribou, but rather that the regional capacity of the landscape for caribou currently falls within the NRV.

During the next three decades, the ALCES simulations indicate a consistent degradation in caribou population response, with populations consistently below a lambda value of 1 within 2.5 decades. The causes of this modelled degradation are the progressive increase in linear and polygonal industrial features and changes in the forest age class structure of the regional landscape. As development in the region continues, access management is identified as the management strategy having the most significant opportunity to mitigate future effects. Specifically, this caribou response to access management reflects the initial pulse reclamation of existing seismic lines and the reduction of human activity on linear features. The model projects that access management could help mitigate development effects, but regional populations would remain in a precarious balance.

5.2.6. Sensitivity Analyses

Indicator performance was forecast at 1) base case, 2) double bitumen production rates, 3) double the reclamation time and 4) double bitumen production and double reclamation time, to test the response of caribou population response to these key modelling uncertainties.

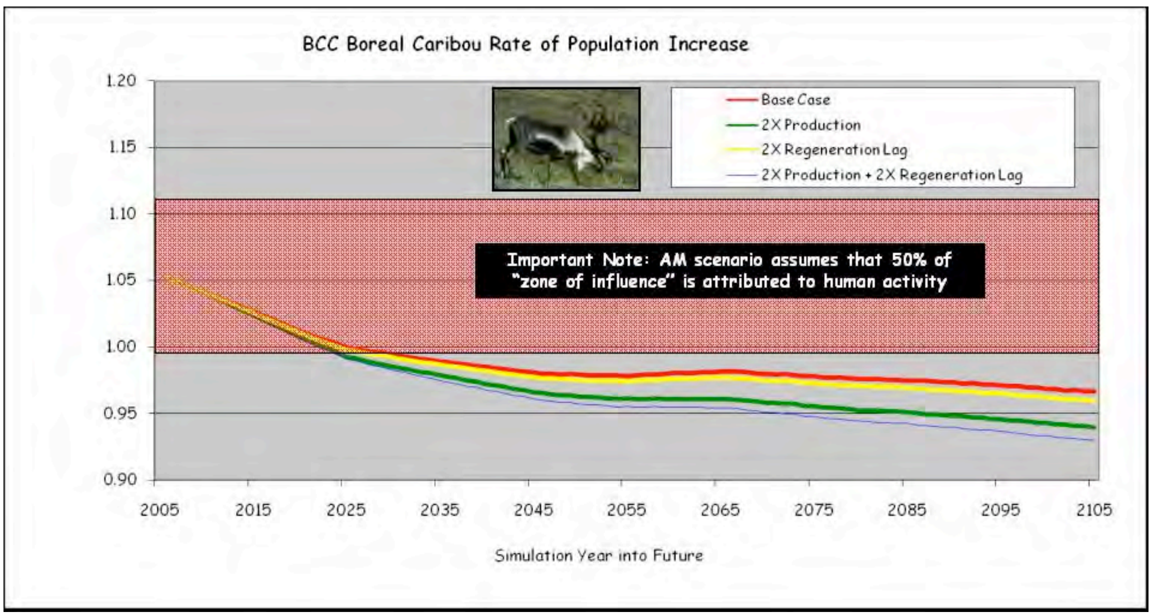

Figure 10: Forecasted Woodland Caribou Population performance in Sensitivity Modelling

The indicator performance is most sensitive to double production and double production and double reclamation lag. The construction of linear features poses the greatest risks to indicator performance and slower reclamation exacerbates the negative effect. All scenarios show a continuing decline below the NRV.

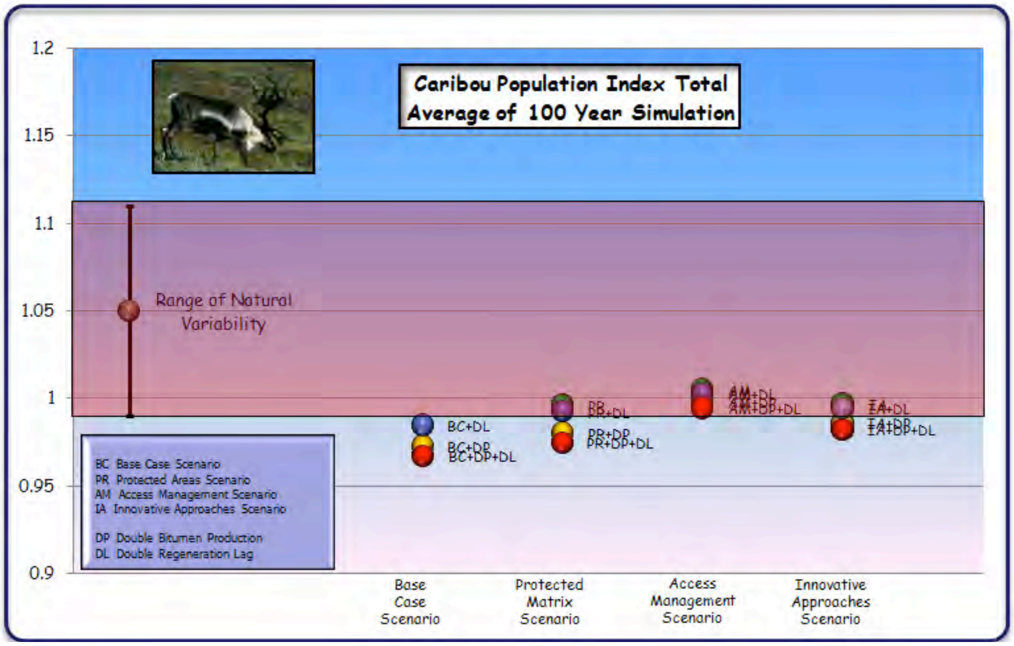

Figure 11: Comparison of Management Strategy effect on the average of Caribou Population forecasted performance over the 100-year planning horizon

While protected areas, access management and innovative approaches all show some potential for mitigating development effects on Woodland Caribou, access management is the most effective management strategy explored.

5.2.7. Herd Management

Spatial assessments of development implications for individual herds were undertaken. Given the importance of stand age as well as linear features, a spatial assessment of forest age class by herd was conducted for the base case, double production and protected areas double production sensitivities. These assessments included anthropogenic as well as fire disturbance on traditional herd ranges within the area:

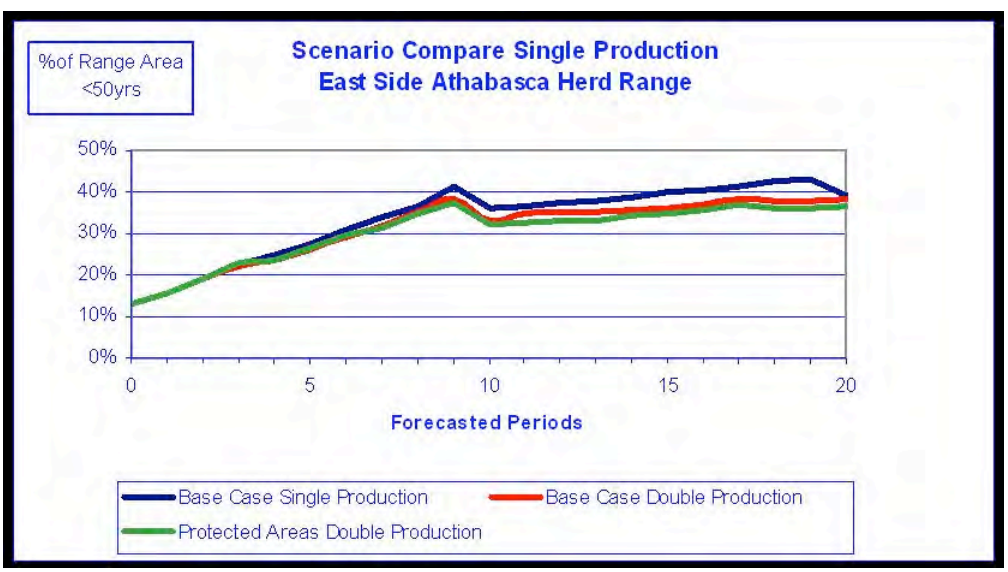

Figure 12: % of East Side Athabasca Herd Range Less Than Fifty Years Old

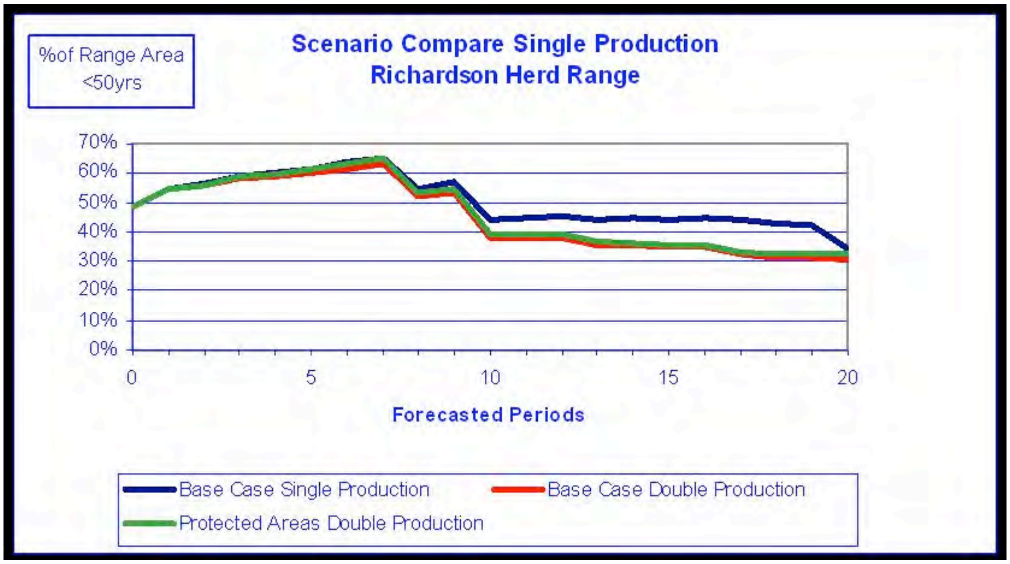

Figure 13: % of Richardson Herd Range Less Than Fifty Years Old

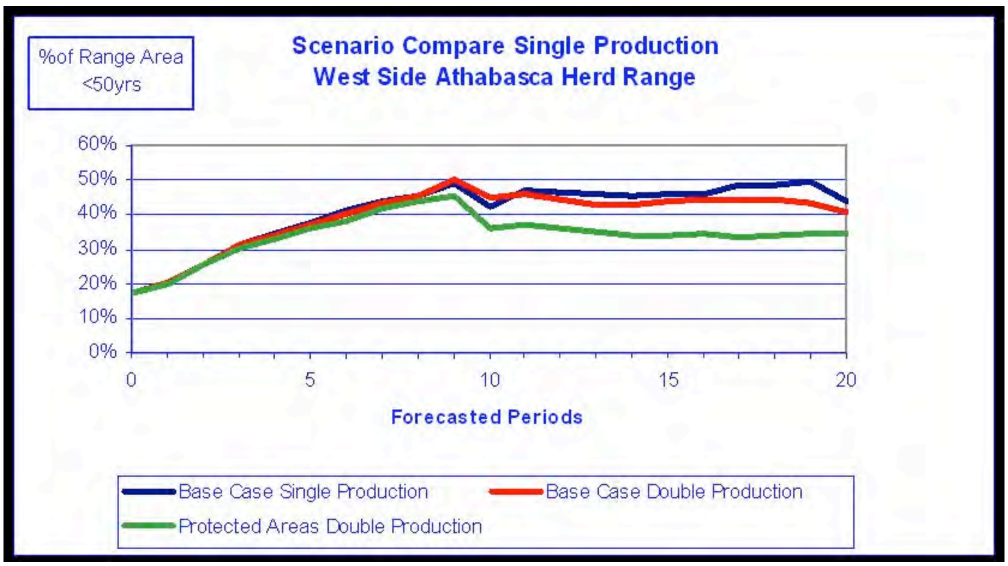

Figure 14: % of West Side Athabasca Herd Range Less Than Fifty Years Old

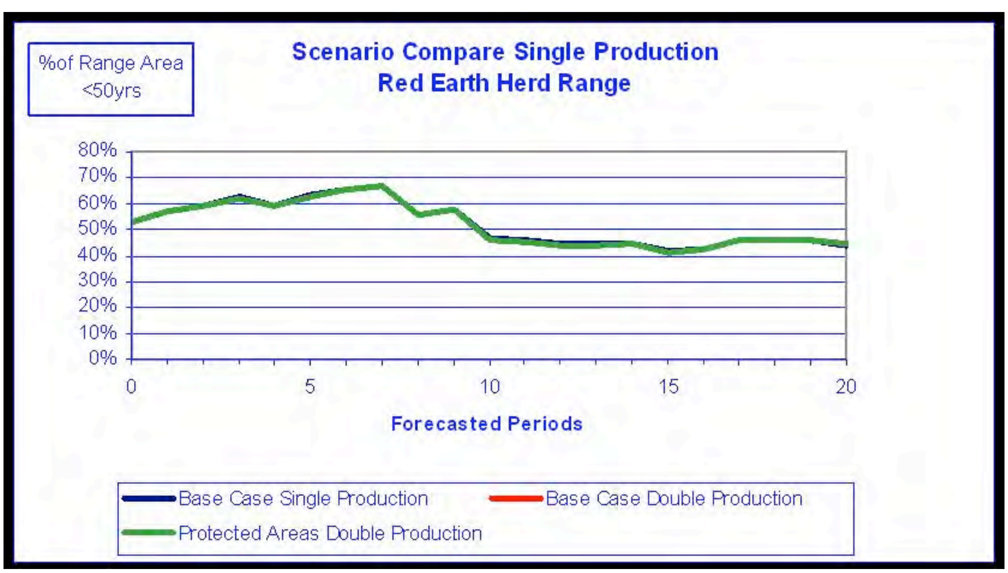

Figure 15: % of Red Earth Herd Range Less Than Fifty Years Old

The Richardson herd range is the most sensitive to doubling production rates while the Red Earth range age class is relatively unchanged. The protected area scenario tested was projected to have the most beneficial effect on the West Side Athabasca herd range age class.

In addition, spatial map models were developed showing projected oilsands development and traditional herd ranges. These maps are available at www.cemaonline.ca

5.2.8. Drivers:

- habitat requirements are specific and highly influenced by stand age and fire history
- Population growth is sensitive to linear features and zone of Influence

5.2.9. Indicator Specific Monitoring Considerations

The lambda equation requires 2 variable inputs as described below:

5.2.9.1. GIS Polygonal and Linear Feature Analysis

% of Range within Zone of Influence and % of Range of insect disturbance or pyrogenic origin and less than 50 years old

5.2.9.2. Field Surveys for monitoring wildlife population and vegetation type

Herd level population monitoring conducted by ACC

5.2.9.3. Level of Integration from ABMI: Moderate

5.2.9.3.1. Habitat:

The current 20 km systematic grid design used by ABMI is expected to to effectively track changes in regional caribou habitat in an unbiased manner by detecting changes in habitat quantity and quality as well as human footprint. In 2008, the ABMI is expected to be able to identify the number of sample sites that will be needed to detect a significant change in caribou habitat.

http://www.abmi.ca/abmi/reports/reports.jsp?categoryId=0

5.2.9.3.2. Population Response:

It is not yet clear to what level ABMI will be able to provide information on changes in caribou abundance. In 2006 snow tract surveys, caribou were detection ranged from 3.8% to 25% of sites surveyed, depending upon habitat utility. The results are preliminary but ABMI will be able to contribute some data. The ABMI has identified two ways to improve its ability to detect significant changes in caribou population response:

- For a given area, increasing the density of ABMI points is the most certain way to increase power and maintain scientifically credible results.
- Harmonizing data collection methods between monitoring initiatives.

5.2.10. Other Identified Organizations:

5.2.10.1. Agency: Alberta Caribou Committee

Activities: Vision is to maintain woodland caribou in Alberta's boreal ecosystem while maintaining opportunities for resource development following the principles set by IL 91-

17. The current and future challenge involves using a knowledge-based process to develop and implement adaptive land-use strategies for industrial activity on designated caribou range in Alberta. These complex ecological challenges will continue to be addressed by the participants in an atmosphere of co-operation and trust.

http://www.albertacariboucommittee.ca

5.2.10.2. Agency: Alberta Sustainable Resource Development

Activities: Alberta's *Wildlife Act* is the provincial legislation that deals with wildlife. Protecting and maintaining suitable habitat is critical in maintaining long-term wildlife health and viability. Similarly, wildlife health is an important indicator of the health of Alberta's environment. The provincial government is committed to conserving wild species and it pays particular attention to those that may be at risk of extinction. Alberta has been involved in programs to identify and restore species at risk for more than 25 years.

http://www.srd.gov.ab.ca/fishwildlife/speciesatrisk/default.aspx

5.2.11. Identified scientific knowledge gaps:

- Utility of the lambda equation approach
- Individual herd management requirements
- Incomplete forest cover inventory across the region
- Utility of building a multi-species predator pit dynamics model involving woodland caribou, moose, and wolves

5.3. *Indicator : Moose habitat and population response*

5.3.1. Indicator Category: Environmental

5.3.2. Goal: Sustain viable and healthy populations of wildlife and fish

5.3.3. Modelled Condition - Green

The regional objective is currently being met and is forecast to stay within 10% below the lower limit of the NRV for at least the next 30 years. Model results do indicate that moose HEI performance could drop to a yellow condition in the long-term, particularly if bitumen production rates are higher than the Base Case Alberta Energy forecast.

5.3.4. Indicator Rationale:

Moose is one of the environmental indicators chosen by SEWG for this project through workshops utilizing agreed upon selection criteria. Moose are an important game species in the north and are a part of key predator-prey interactions as well as being an important species for Aboriginal Traditional Land Use.

5.3.5. Indicator Natural Range of Variability:

The NRV was determined from 50 stochastic ALCES runs using a back-casted dataset. A localized moose habitat effectiveness index (HEI) was developed for this study and utilized directly in the ALCES modelling. An index value of 1 indicates ideal conditions of moose habitat and utility. An index value of 0 would represent no moose populations or habitat present. The natural range acknowledges that conditions are not always ideal and that the index could be expected to fluctuate naturally between 0.4 and 0.49.

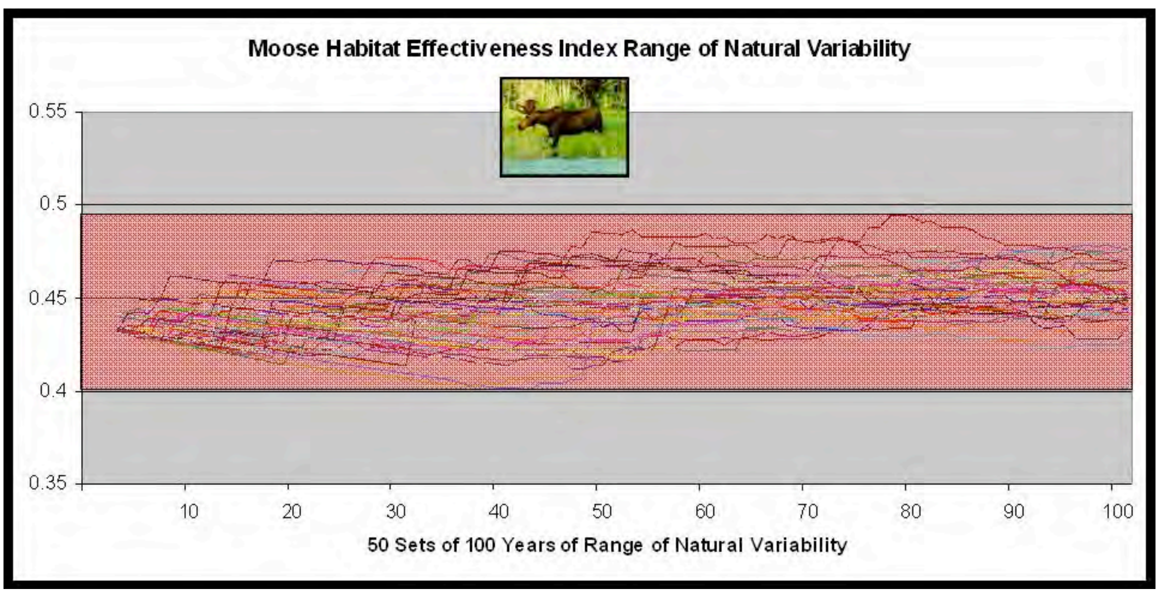

Figure 16: Moose Habitat Effectiveness Natural Range of Variability

5.3.6. Forecasted Scenario Outcomes for Moose:

The graph below shows the forecasted indicator performance using a localized ALCES sub-model of Moose HEI with the NRV as a reference point. Scenarios forecast include the Base Case, Innovative Approaches, Protected Area and Access Management.

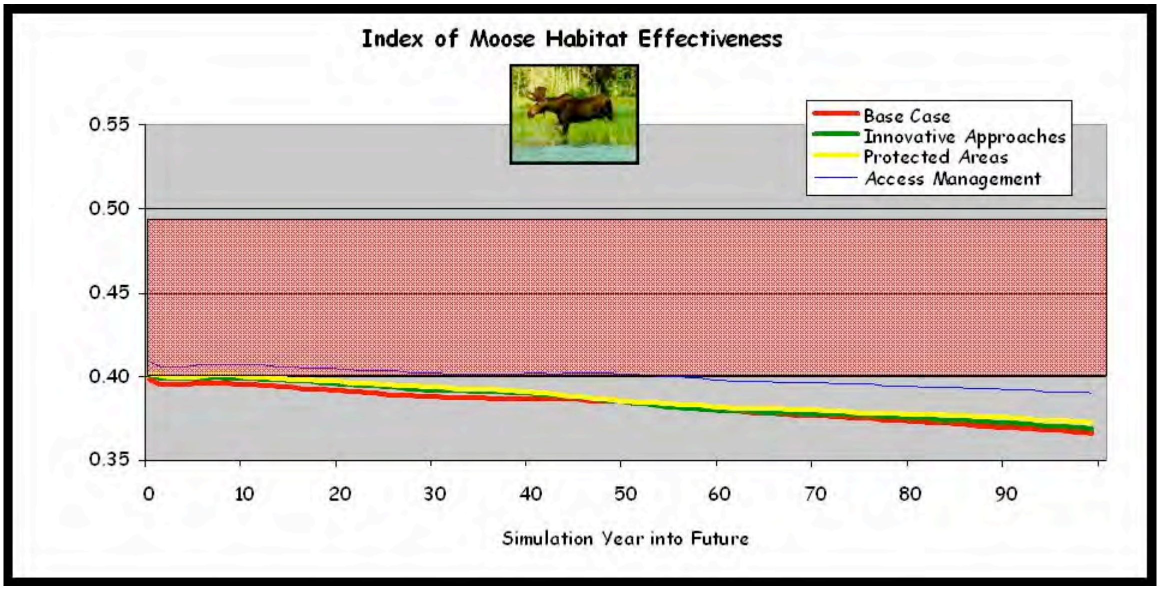

Figure 17: Forecasted Moose HEI performance in Main Program Modelling

Currently, moose habitat effectiveness is forecast to be at the lower limit of NRV primarily due to the existence of roads and seismic lines and a high degree of human access on them. The general trend under all scenarios is a very slow decline to levels below the NRV. Access management is forecast to be the most effective mitiagation strategy to minimize development impacts. In the absence of access management, modelling suggests the moose HEI could decline by 18% over the next century.

5.3.7. Sensitivity Analyses

Indicator performance was forecast at double bitumen production rates, double the reclamation time and both double bitumen production and double reclamation time to test the risk associated with these key modelling uncertainties. The slight difference in the Base Case performance in these results from that forecast in the Main Program Modelling arises because of sub-model refinements in-between phases.

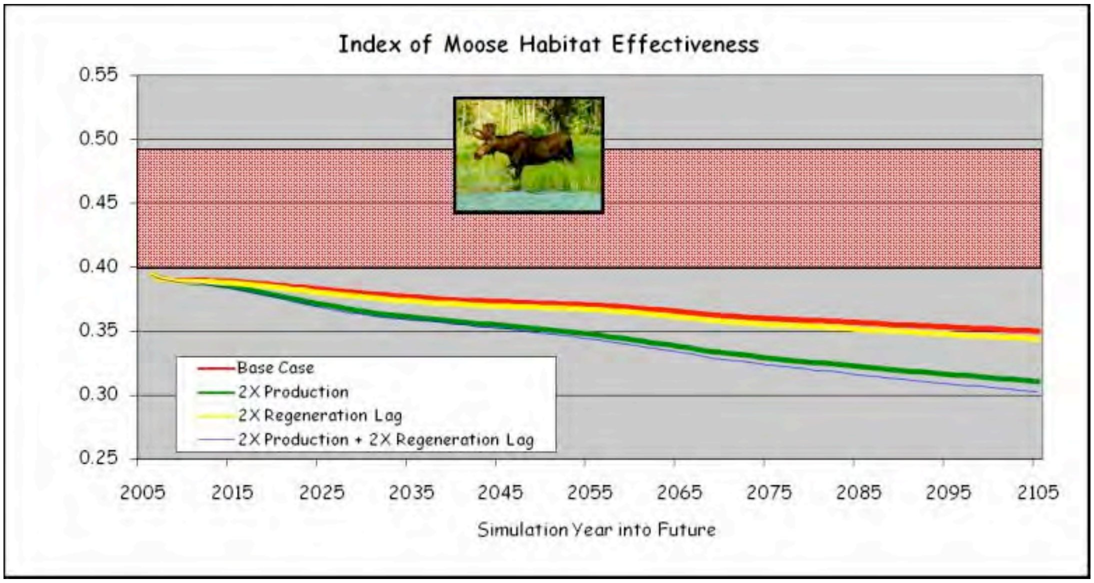

Figure 18: Forecasted Moose HEI performance in Sensitivity Modelling

Indicator performance is most sensitive to double production. The construction of linear features poses the greatest risks to indicator performance and slower reclamation does slightly increase the negative effect. All scenarios show a departure below the NRV. When double reclamation period is combined with double bitumen production rates, forecasted indicator performance falls to approximately 33% below the lower limit of NRV over the 100 year forecast period.

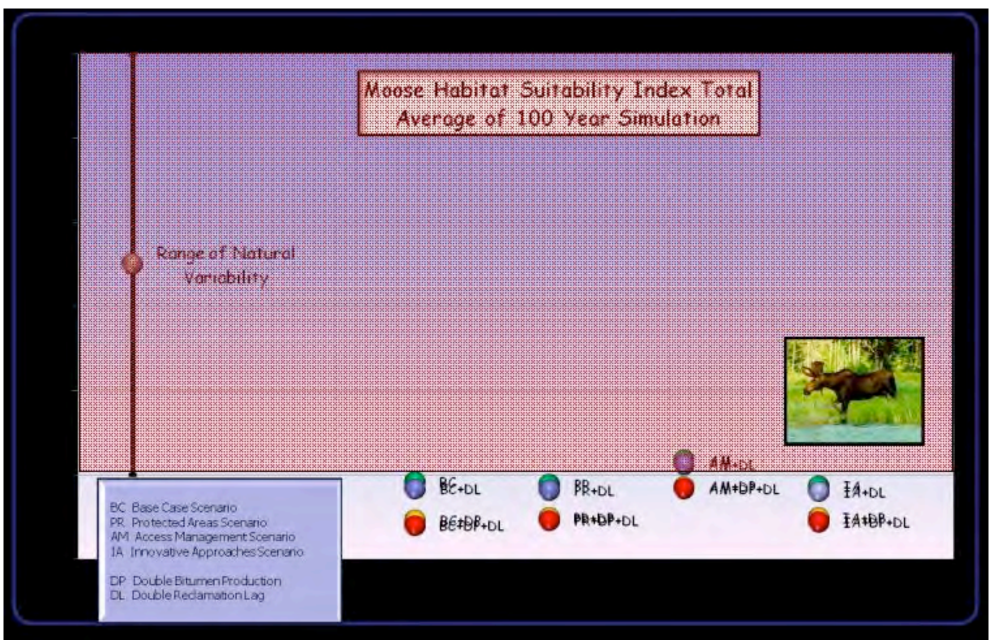

Figure 19: Comparison of Management Strategy effect on the average of Moose HEI forecasted performance over the 100 year planning horizon

Access management is forecast to be the most effective mitiagation strategy to minimize development impacts and is able to largely offset double production impacts. The key reason for this is that mortality from humans, the primary downward pressure on populations, is reduced with effective access management.

Moose harvest forecasts were generated using an existing ratio-estimater in ALCES. Annual moose harvest rate forecasts suggest that between 1500 – 1625 animals could be harvested per year on average.

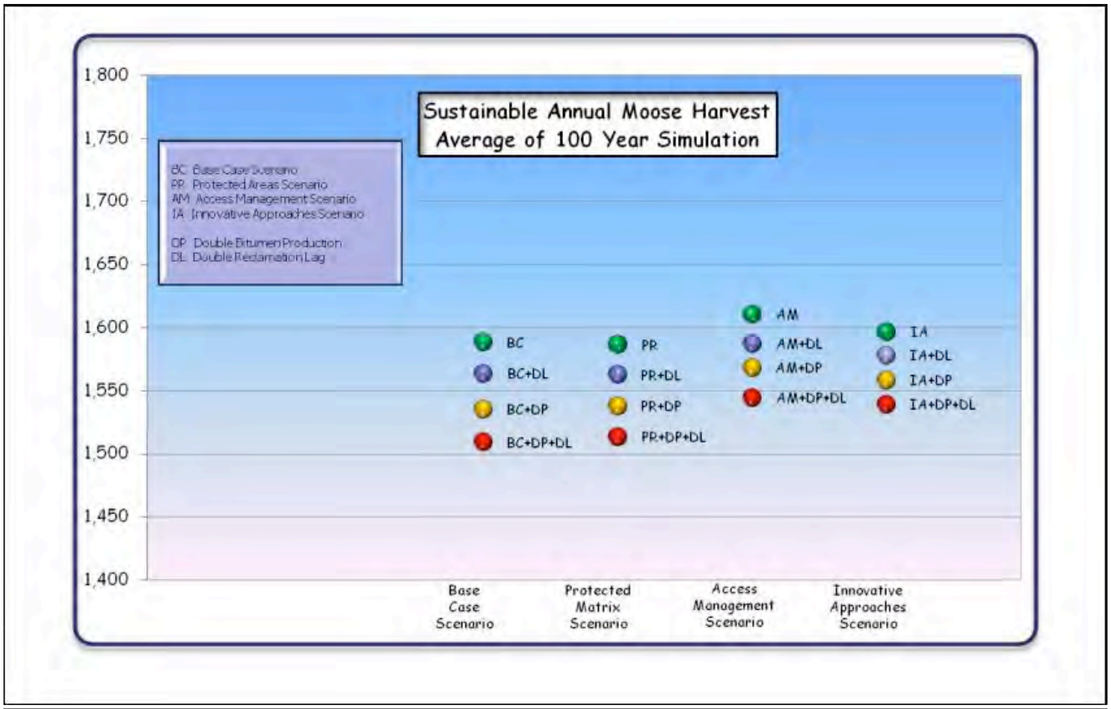

Figure 20: Average Annual Moose Harvest Forecasts

5.3.8. Drivers:

- Sensitive to habitat type and age - younger, shrub-dominated stands preferred
- Moderately sensitive to Linear Features and Zone of Influence if there is no access management

5.3.9. Indicator Specific Monitoring Considerations

The Moose HEI requires 10 variable inputs as described below:

5.3.9.1. GIS Polygonal and Linear Feature Analysis

Area by Landscape Type, Footprint Type, and seral stage, road density and shrub density

5.3.9.2. Models and Assumptions

Habitat Quality of each Landscape Type and Footprint Type, Buffer Width for Zone of Influence, forest structure value

5.3.9.3. Government Agency Captured Information

Human density (# people/km^2)

5.3.9.4. Level of Integration from ABMI:

5.3.9.4.1. Habitat: High

The ABMI sampling approach to track change in moose habitat quantity and quality and human footprint is expected to be very effective at the 1 million ha level which is well within the level of resolution necessary for TEMF monitoring.

http://www.abmi.ca/abmi/reports/reports.jsp?categoryId=0

5.3.9.4.2. Population Response: High

The ABMI expected to be very effective monitoring changes in moose abundance throughout the region.

In addition to the number of sites, years, trends, power to detect trend for each species is affected by:

- Occurrence – the range, abundance and prevalence on the landscape. This is affected primarily by habitat and physiography.
- Detectability - the ability to detect the animals when they are there which is a combination of species characteristics and methodology.

Preliminary estimates of the number of ABMI sites required to detect change in abundance assuming a desire to attain a power of 0.9 or greater to detect an annual decrease of 3% over 15 years of monitoring.

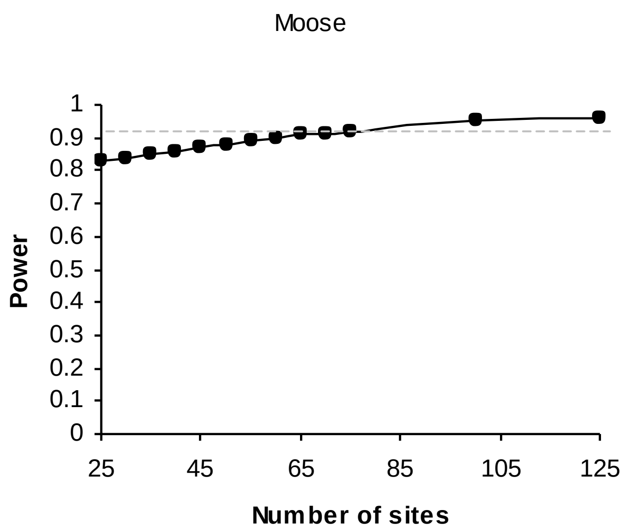

Figure 21: ABMI Moose detectability[3]

Moose are easily detected given their distinct tracks. Good statistical power (0.83) is achieved with 25 sites representing an area of 1 million ha. Power increases to 0.85 with 35 sites and reaches 0.9 at approximately 70 sites or 2.8 million ha.

Power was estimated using a predictive equation built with prototype data, using parameters for each species that ABMI studied as part of an in-situ monitoring pilot project. These are considered to reflect "worst case scenarios". These power estimates don't take into account abundance changes or how power will change as by combining occurrence and abundance into an index (which is predicted to increase power).

5.3.10. Other Identified Organizations:

5.3.10.1. Agency: Alberta Fish and Wildlife

Activities: AFW manages moose as a game species, setting quotas for allowable hunts based on trend information.

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[3] source: ABMI

http://www.srd.gov.ab.ca/fishwildlife/livingwith/huntingalberta/default.aspx

5.3.10.2. Agency: Alberta Conservation Association

Activities: Northern Moose Management Program (early 2000's). The Northern Moose Management Program (NMMP) was initiated in 1993 in response to concerns expressed by subsistence and recreational hunters about declining moose numbers. Funded through the ACA, the program was established to answer questions about moose population dynamics and to identify the management actions required to stabilize or improve moose numbers in Moose Management Areas (MMAs) 5— 9.

http://www.srd.gov.ab.ca/fishwildlife/livingwith/huntingalberta/northernmoosemanagement/

5.3.11. Identified scientific knowledge gaps:

- Spatial distribution of populations
- RSF model for the RMWB
- Wildlife Movement Corridors

5.4. Indicator: Fisher

5.4.1. Indicator Category: Environmental

5.4.2. Goal: Sustain viable and healthy populations of wildlife and fish

5.4.3. Modelled Condition - Yellow

Indicator is forecast to fall below NRV within the next 30 years under a base case scenario.

5.4.4. Indicator Rationale:

Fisher is one of the environmental indicators chosen by SEWG for this project through workshops utilizing agreed upon selection criteria. Fisher are a low-density furbearer possessing specific habitat requirements involving stand age and forest structure. Concern exists that this important furbearer may be declining in abundance and distribution.

5.4.5. Indicator Natural Range of Variability:

The NRV for fisher habitat effectiveness values was determined by conducting fifty 100-year stochastic simulations in ALCES run on the pre-industrial landscape driven by natural disturbance regimes. An index value of 1 represents a landscape comprised of preferred habitat types containing preferred physiognomy (age class and forest structure). An index value of 0 would represent a landscape possessing no useful habitat for fisher. The natural range acknowledges that conditions are not always ideal and that the index could be expected to fluctuate naturally between 0.08 and 0.14. The low NRV values for fisher indicate that much of the RMWB is not suitable as fisher habitat because it is non-forested or does not contain the required forest structural elements.

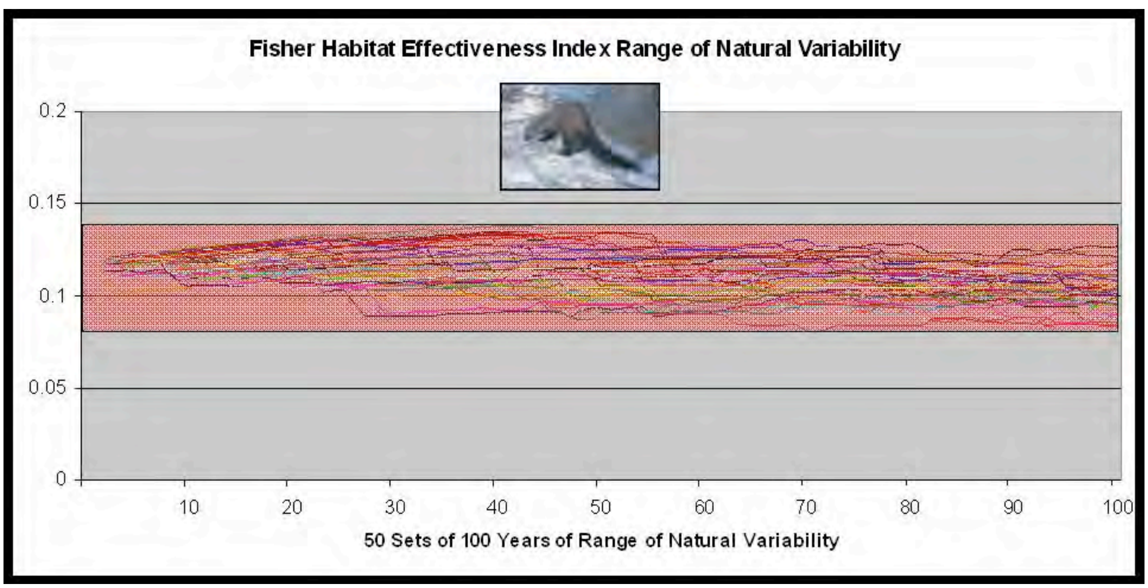


Figure 22: Fisher HEI Integrity Natural Range of Variability

5.4.6. Forecasted Outcomes for Fisher Habitat Effectiveness Index:

The graph below shows the forecasted indicator performance using the ALCES model of Fisher Habitat Effectiveness Index with the NRV as a reference point. Scenarios forecast include the base case, innovative approaches, a comprehensive protected area and access management.

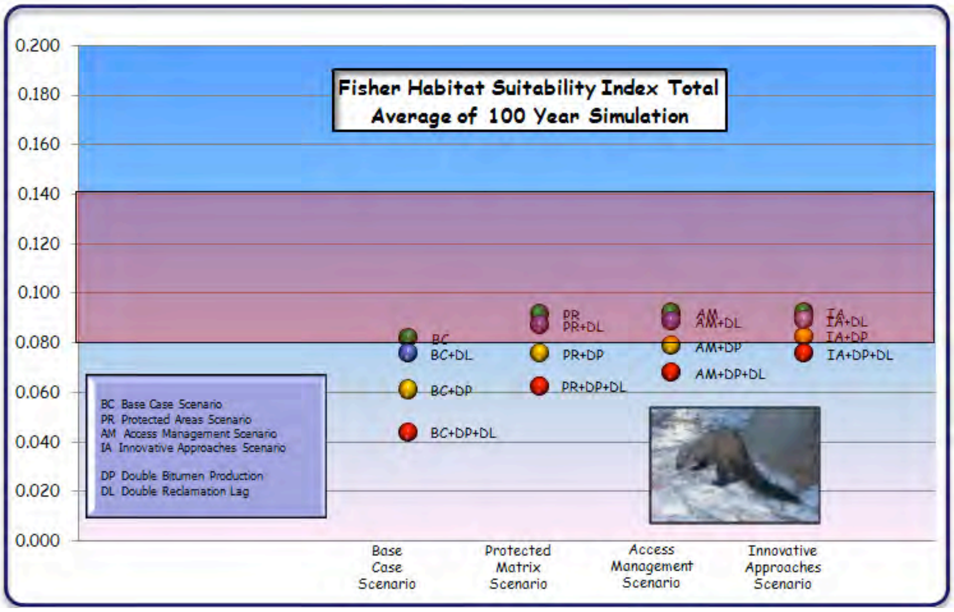


Figure 23: Comparison of Management Strategy effect on the average of Fisher HEI forecasted performance over the 100 year planning horizon

Average performance of fisher habitat integrity over the next 100 years, under a base case scenario (green dot above), approximates the lower range of NRV. Relative to the base case, a modest improvement in indicator performance, at the scale of the RMWB, occurs for each of protected areas, access management and innovative approaches. Although the benefits of protected areas to fisher appears to be modest, it is important to realize that the effects are area-weighted across the RMWB. A comparison of fisher habitat integrity within the protected areas and within the “intensive” industrial areas better contrasts the value of protected areas to fisher.

As seen below, fisher habitat integrity inside the protected areas remains within the NRV for the full simulation interval, whereas integrity within the intensively managed (insitu and surface mining) portion of the landscape starts at a much lower value and quickly descends well below NRV. The effects of increasing bitumen production and regeneration lag of footprints is also illustrated in this comparison.

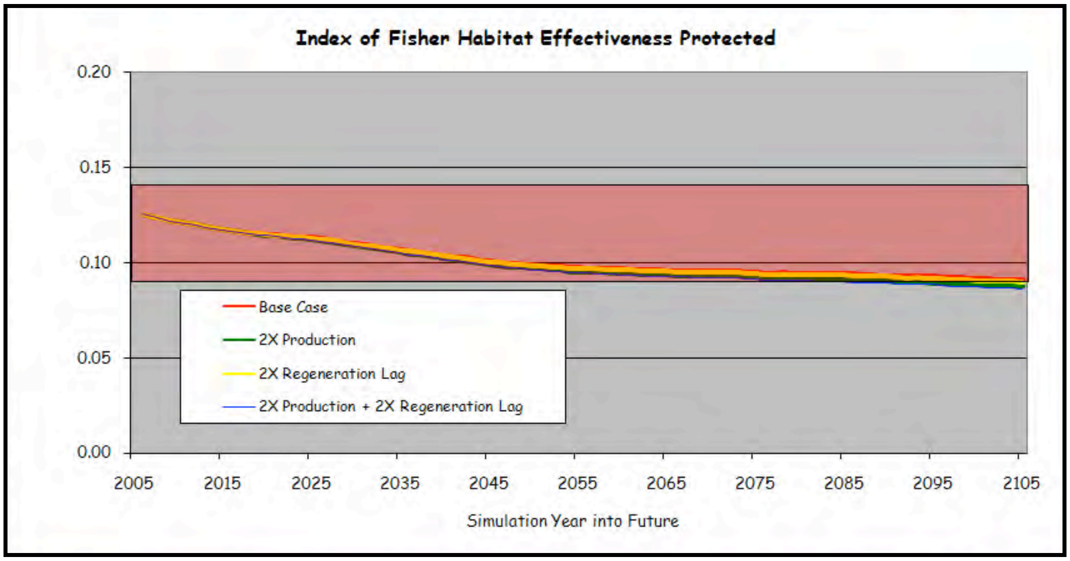


Figure 24: Forecasted Fisher HEI performance in Protected Zone

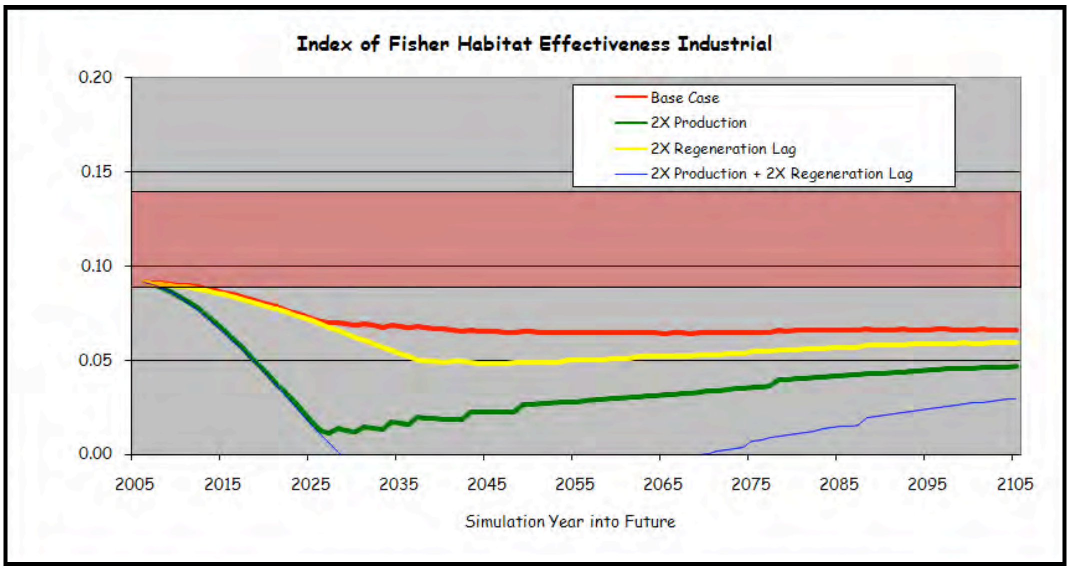


Figure 25: Forecasted Fisher HEI performance in Intensive Zone

5.4.7. Sensitivity Analyses

Indicator performance was forecast at double bitumen production rates, double the reclamation time and both double bitumen production and double reclamation time to assess the risk to fisher habitat integrity associated with these key modelling uncertainties.

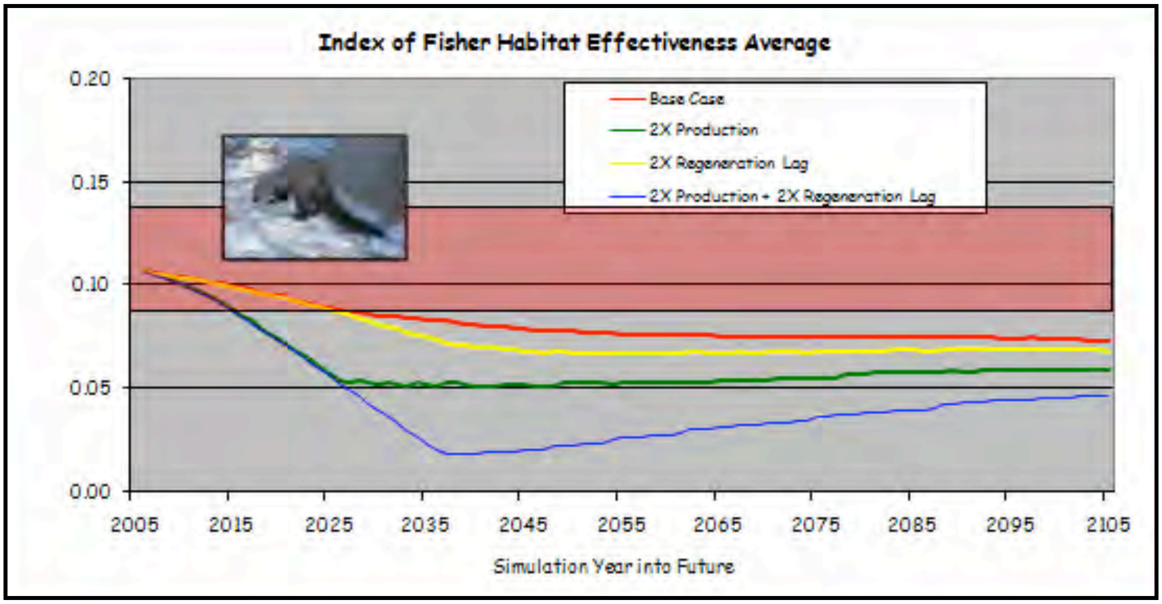


Figure 26: Forecasted Fisher HEI performance in Sensitivity Modelling

Fisher habitat integrity is significantly sensitive to all three uncertainty scenarios. Expectedly, fisher respond most poorly to a scenario where bitumen production is doubled and regeneration lag is doubled. This is the scenario that creates the most linear and polygonal footprint on the landscape. This combination would lead to the loss of over 80% of current habitat integrity on the RMWB by 2040.

5.4.8. Key Indicator Performance Drivers:

- Selective to Forest Habitat Types
- Very sensitive to Stand Age (older stands preferred)
- Sensitive to Linear Features and Zone of Influence (ZOI)
- Very sensitive to increased bitumen production and increased Reclamation lag

5.4.9. Indicator Specific Monitoring Considerations

The Fisher HEI requires 10 variable inputs as described below:

5.4.9.1. GIS Polygonal and Linear Feature Analysis

Area by Landscape Type, Footprint Type, and seral stage, road density and shrub density

5.4.9.2. Models and Assumptions

Habitat Quality of each Landscape Type and Footprint Type, Buffer Width for Zone of Influence, forest structure value

5.4.9.3. Government Agency Captured Information

Human density (# people/km^2)

5.4.9.4. Level of Integration from ABMI:

5.4.9.4.1. Habitat: High

The ABMI sampling approach to track change in fisher habitat quantity and quality and human footprint is expected to be very effective at the 1 million ha level which is well within the level of resolution necessary for TEMF monitoring.

http://www.abmi.ca/abmi/reports/reports.jsp?categoryId=0

5.4.10. Population Response: High

The ABMI expected to be very effective monitoring changes in fisher abundance throughout the region.

In addition to the number of sites, years, trends, power to detect trend for each species is affected by:

- Occurrence – the range, abundance and prevalence on the landscape. This is affected primarily by habitat and physiography.
- Detectability - the ability to detect the animals when they are there which is a combination of species characteristics and methodology.

Preliminary estimates of the number of ABMI sites required to detect change in abundance assuming a desire to attain a power of 0.9 or greater to detect an annual decrease of 3% over 15 years of monitoring.

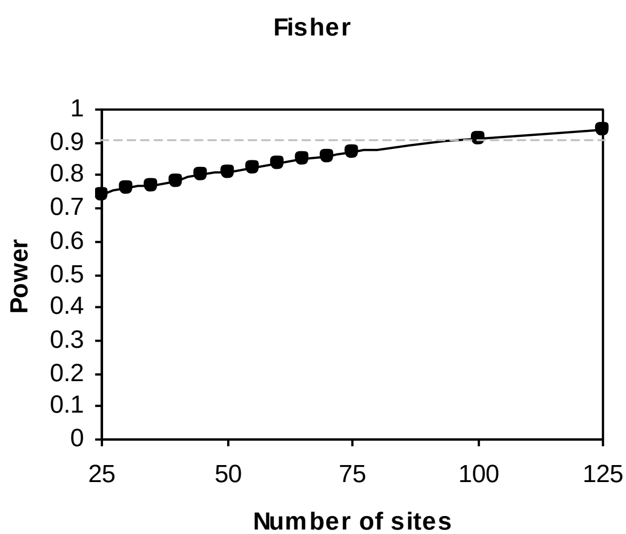


Figure 27:ABMI fisher detectability[4]

Fisher are more difficult to detect than other species as their tracks are easily confused with those of Marten. Nonetheless, reasonable statistical power (0.74) is achieved with 25 sites representing an area of 1 million ha. Power increases to 0.85 with 65 sites or 2.6 million ha.

Power was estimated using a predictive equation built with prototype data, using parameters for each species from the SAGD pilot. These are considered to reflect "worst case scenarios". These power estimates don't take into account abundance changes or

[4] source: ABMI

how power will change as by combining occurrence and abundance into an index (which is predicted to increase power).

5.4.11. Other Identified Organizations:

5.4.11.1. Agency: Alberta Fish and Wildlife

Activities: AFW manages fishers as a furbearer species, setting quotas for allowable hunts based on trend information.

http://www.srd.gov.ab.ca/fishwildlife/livingwith/huntingalberta/default.aspx

5.4.11.2. Agency: Alberta Trappers Association

Activities: Fisher harvest; contribute to management and sometimes research.

http://www.albertatrappers.com/

5.4.11.3. Agency: Alberta Research Council, Sustainable Ecosystems, Jason Fisher

Activities: ARC is currently conducting a 5-year research program on fisher occupancy and habitat selection in the Alberta foothills, with the results to be made available to AFW and published late 2008. Alberta Conservation Association is a majority partner in this endeavour.

http://www.arc.ab.ca/index.aspx/ARC/598

5.4.12. Identified scientific knowledge gaps:

- Calibration of habitat suitability model approach with actual empirical fisher abundance data
- Fisher response surface to pyrogenic and logged forest
- Effect of access management on mortality factors (trappers) to fisher

5.5. Indicator: Old Growth Forest Birds Habitat Effectiveness

5.5.1. Indicator Category: Environmental

5.5.2. Goal: Sustain viable and healthy populations of wildlife and fish

5.5.3. Modelled Condition - Green

Indicator is forecast to remain within the NRV for the simulation interval.

5.5.4. Indicator Rationale:

Old Growth Forest Bird Habitat Effectiveness is one of the environmental indicators chosen by SEWG for this project through workshops utilizing agreed upon selection criteria. Old forest birds have been widely used by ecologists as responsive indicators to landscapes that are becoming younger and fragmented. The index algorithm was developed through a combination of literature review and Delphi process conducted by Tanya Hope and Dr. Erin Bayne of the University of Alberta.

5.5.5. Indicator Natural Range of Variability:

The NRV for old growth forest bird habitat effectiveness values was determined by conducting fifty 100-year stochastic simulations in ALCES run on the pre-industrial landscape driven by natural disturbance regimes. Current conditions were indexed to 1.0 to allow for scenario comparisons. Relative to current conditions, NRV varied between 0.9 and 1.1, reflecting inter-annual variation in forest age class structure generated by a natural stochastic fire regime. Old growth forest bird habitat effectiveness as defined here varies less than the measure of old forest (see 5.7 below). The bird species selected as part of this multi-species indicator collectively cover a wide range of habitat preferences and tolerances and are not old growth obligates. As a consequence the indicator is relatively non-responsive to changes in forest structure.

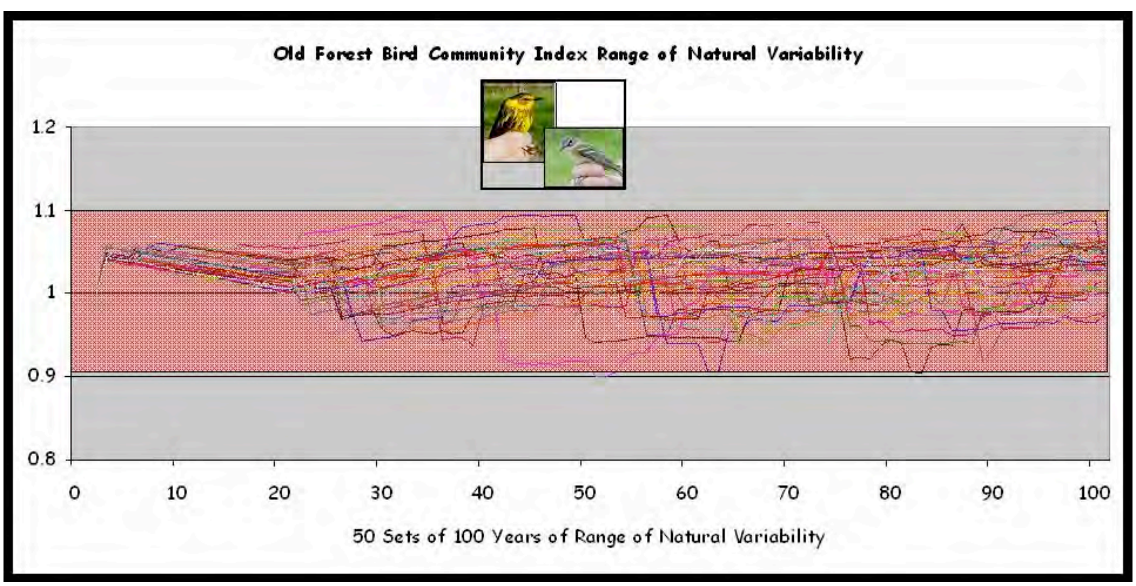


Figure 28: Old Forest Bird Community Index Natural Range of Variability

5.5.6. Forecasted Scenario Outcomes for Fisher Habitat Effectiveness index:

The graph below shows the forecasted indicator performance using the ALCES model of Old Forest Bird Habitat Effectiveness Index with the NRV as a reference point. Scenarios forecast include the Base Case, Innovative Approaches, Protected Areas and Access Management.

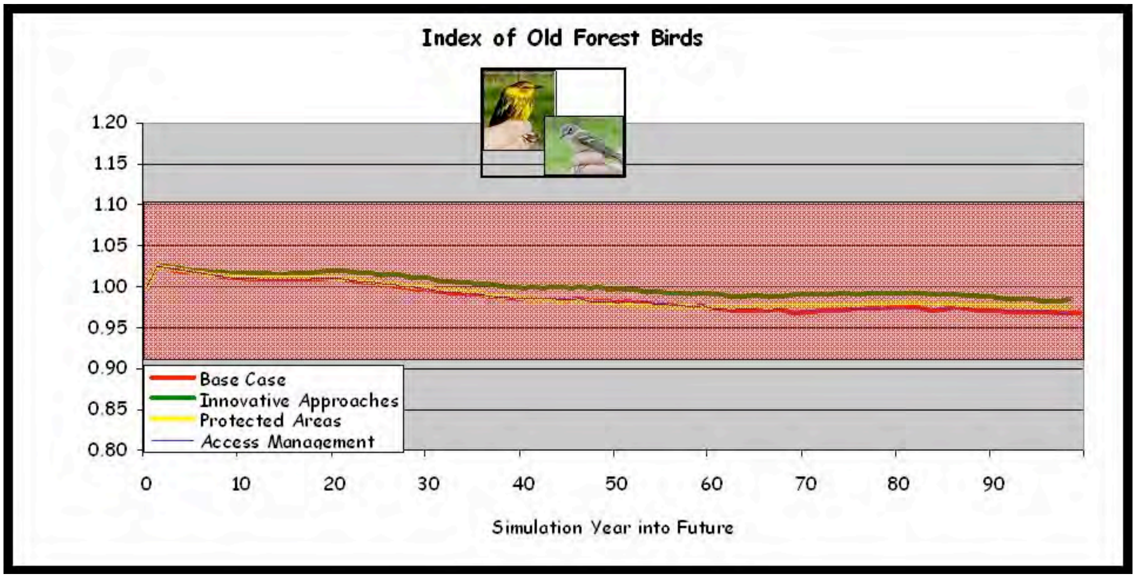


Figure 29: Forecasted Old Forest Bird Community Index performance in Main Program Modelling

Under all scenarios, the integrity of old forest bird habitat remains well within NRV and illustrates minimal difference between the scenarios. This bird guild seems relatively non-responsive to changes in forest age class structure or increasing linear edge density.

5.5.7. Sensitivity Analyses

Indicator performance was forecast at double bitumen production rates, double the reclamation time and both double bitumen production and double reclamation time to test the risk associated with these key modelling uncertainties.

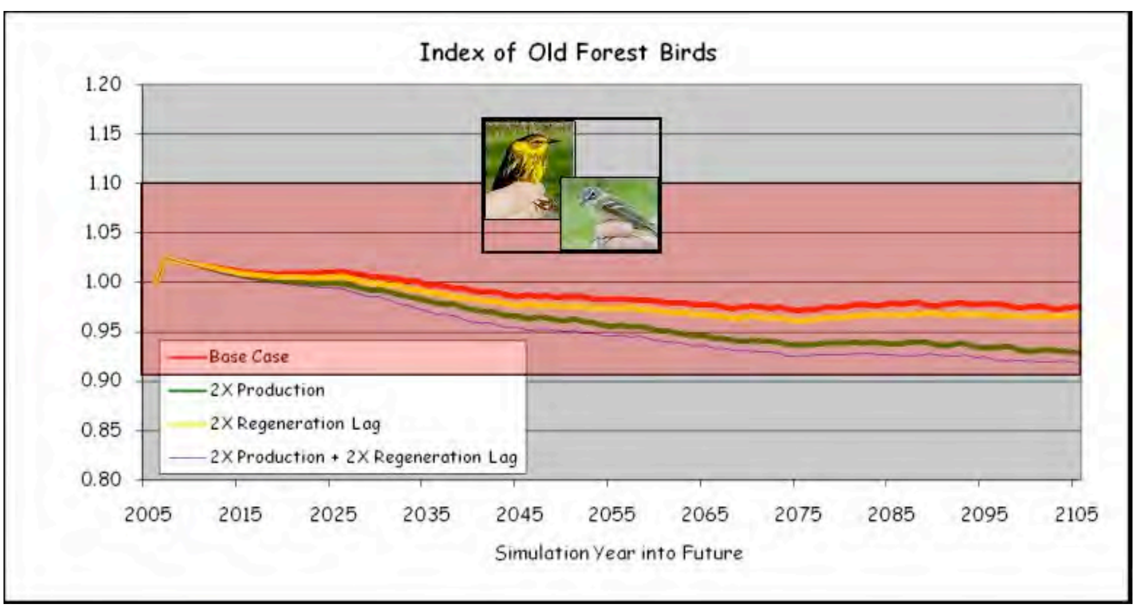


Figure 30: Forecasted Old Forest Bird performance in Sensitivity Modelling

As shown above, index of old forest bird integrity does decline once the landscape is subjected to combinations of double bitumen production and double regeneration lag. Despite these gradual declines, this index remains within NRV for the full 100-years.

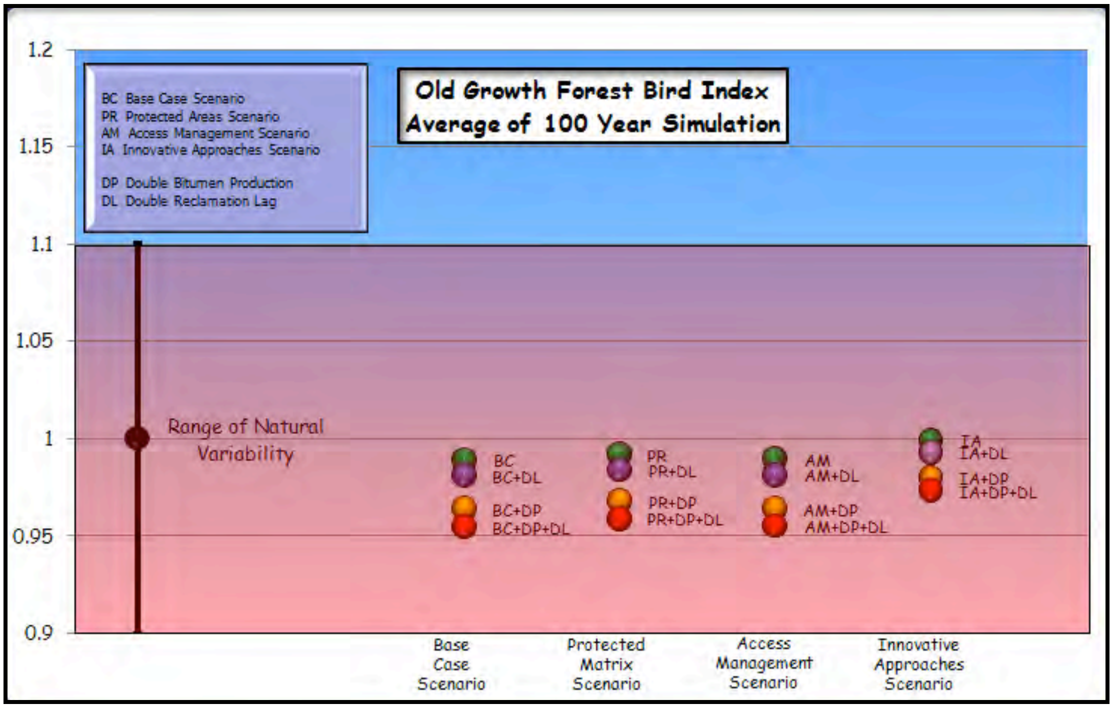


Figure 31: Comparison of Management Strategy effect on the average of Old Forest Bird Community Richness Index forecasted performance over the 100-year planning horizon

The graph above illustrates clearly that old forest bird index is more sensitive to the amount of bitumen production (and associated footprint) than to different management scenarios. This guild does not respond notably to protected areas or to access management. The slight improvement observed with innovative approaches can be attributed to the faster reclamation of linear features.

5.5.8. Key Indicator Performance Drivers:

- Selective to Forest Habitat Types
- Moderately sensitive to Stand Age (older stands preferred), but species are moderately abundant across a broad range of seral stages.
- Moderately sensitive to Linear Features and Zone of Influence (ZOI)
- Relative insensitive to increased bitumen production and increased reclamation lag

5.5.9. Indicator Specific Monitoring Considerations

The Old Forest Bird Community Richness Index requires 12 variable inputs as described below:

5.5.9.1. GIS Polygonal and Linear Feature Analysis

Area by Landscape Type, Footprint Type, and seral stage, edge density, natural disturbances especially fire and cultivation

5.5.9.2. Models and Assumptions

of species in guild and whether they are old seral specialists or generalists, Habitat Quality of each Landscape Type and Footprint Type, Buffer Width for Zone of Influence, forest structure value

5.5.9.3. Government Agency Captured Information

Human density (# people/km^2)

5.5.9.4. Level of Integration from ABMI:

5.5.9.4.1. Habitat: High

The ABMI sampling approach to track change in old forest bird habitat quantity and quality and human footprint is expected to be very effective at the 1 million ha level which is well within the level of resolution necessary for TEMF monitoring.

http://www.abmi.ca/abmi/reports/reports.jsp?categoryId=0

5.5.9.4.2. Population Response: High

The ABMI is expected to be very effective monitoring changes in old forest bird abundance throughout the region. Following are the results of initial estimates of the ABMI power to track the occurrence of species that ABMI has identified as within the old growth guild from the SAGD pilot study.

Code	Common Name	Power
YRWA	Yellow-rumped Warbler	0.99
SWTH	Swainson's Thrush	0.97
RCKI	Ruby-crowned Kinglet	0.97
MAWA	Magnolia Warbler	0.8
WIWR	Winter Wren	0.76
LEFL	Least Flycatcher	0.71
YBSA	Yellow-bellied Sapsucker	0.62
WWCR	White-winged Crossbill	0.62
BBWA	Bay-breasted Warbler	0.61
RBGR	Rose-breasted Grosbeak	0.55
RBNU	Red-breasted Nuthatch	0.55
WETA	Western Tanager	0.52
PISI	Pine Siskin	0.4
BHVI	Blue-headed (Solitary) Vireo	0.4
BOCH	Boreal Chickadee	0.4
WAVI	Warbling Vireo	0.38
CMWA	Cape May Warbler	0.35

PIWO	Pileated Woodpecker	0.31
HAWO	Hairy Woodpecker	0.23

Currently, the full predictive power of the guild cannot be predicted until further work is completed by the ABMI. Nonetheless, because of the structure of the ABMI approach, estimation power increases at the guild level and as such there is significant confidence in the potential to estimate guild abundance.

5.5.10. Other Identified Organizations:

5.5.10.1. Agency: Alberta Sustainable Resource Development

Activities: Alberta's *Wildlife Act* is the provincial legislation that deals with wildlife. Protecting and maintaining suitable habitat is critical in maintaining long-term wildlife health and viability. Similarly, wildlife health is an important indicator of the health of Alberta's environment. The provincial government is committed to conserving wild species and it pays particular attention to those that may be at risk of extinction.

http://www.srd.gov.ab.ca/fishwildlife/wildlifeinalberta/default.aspx

5.5.10.2. Agency: University of Alberta, Dept. of Biological Sciences, Dr. Erin Bayne

Activities: Research centers on understanding the cumulative ecological impacts of human activities on boreal forest biodiversity and using GIS to spatially model these effects. Recent research focuses on: 1) behavioral, population, and community responses of boreal forest birds to energy sector development; 2) development of biotic and abiotic ecological indicators for detecting cumulative effects thresholds; and 3) anthropogenic factors influencing the invasion potential of boreal forest landscapes by non-native species and the consequences of invasion to native taxa.

http://www.biology.ualberta.ca/faculty/erin_bayne/?Page=2839

5.5.11. Identified scientific knowledge gaps:

- Empirically defensible dataset linking bird species and populations to different forest seral stages
- The selection of species used to define the guild should be reviewed, and consideration given to modeling a smaller number of species known to true old forest obligates
- Uncertainty as to what width of linear features birds respond to.

5.6. Indicator: Black Bear

5.6.1. Indicator Category: Environmental

5.6.2. Goal: Sustain viable and healthy populations of wildlife and fish

5.6.3. Modelled Condition - Yellow

Black Bear is determined to be in a Yellow Condition because modelling predicts it will drop more than 10% below the lower limit of the NRV within 30 years. Modelling also suggests it is likely that this indicator could move to a red condition in about 30 years under Base Case assumptions.

5.6.4. Indicator Rationale:

Black Bear is one of the environmental indicators chosen by SEWG for this project through workshops utilizing agreed upon selection criteria. Black Bears are an important species in the north both as a vital component of ecosystems as well as from a traditional land use perspective.

5.6.5. Indicator Natural Range of Variability:

The NRV was determined from 50 stochastic ALCES runs using a back-casted dataset. An index value of 1 represents the perfect combination of habitat and population to represent maximum Black Bear HEI. An index value of 0 would represent no Black Bear populations or habitat present. The natural range acknowledges that conditions are not always ideal and that the index could be expected to fluctuate naturally between 0.019 and 0.24.

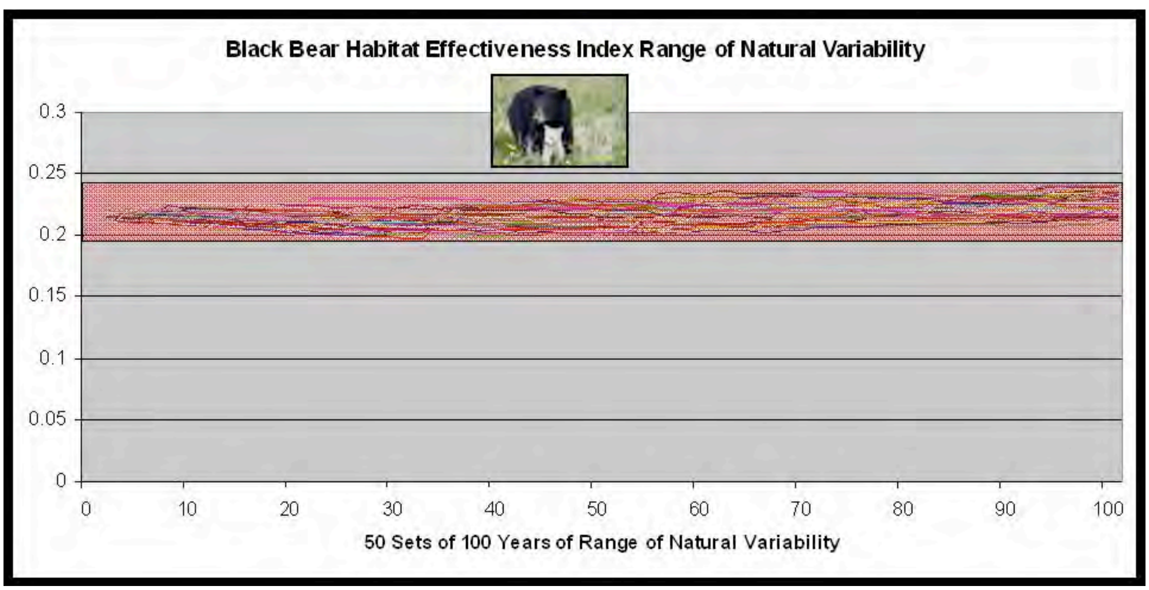


Figure 32: Black Bear HEI Natural Range of Variability

5.6.6. Forecasted Scenario Outcomes for Black Bear HEI:

The graph below shows the forecasted indicator performance using a localized ALCES sub-model of Black Bear HEI with the NRV as a reference point. Scenarios forecast include the Base Case, Innovative Approaches, Protected Area and Access Management.

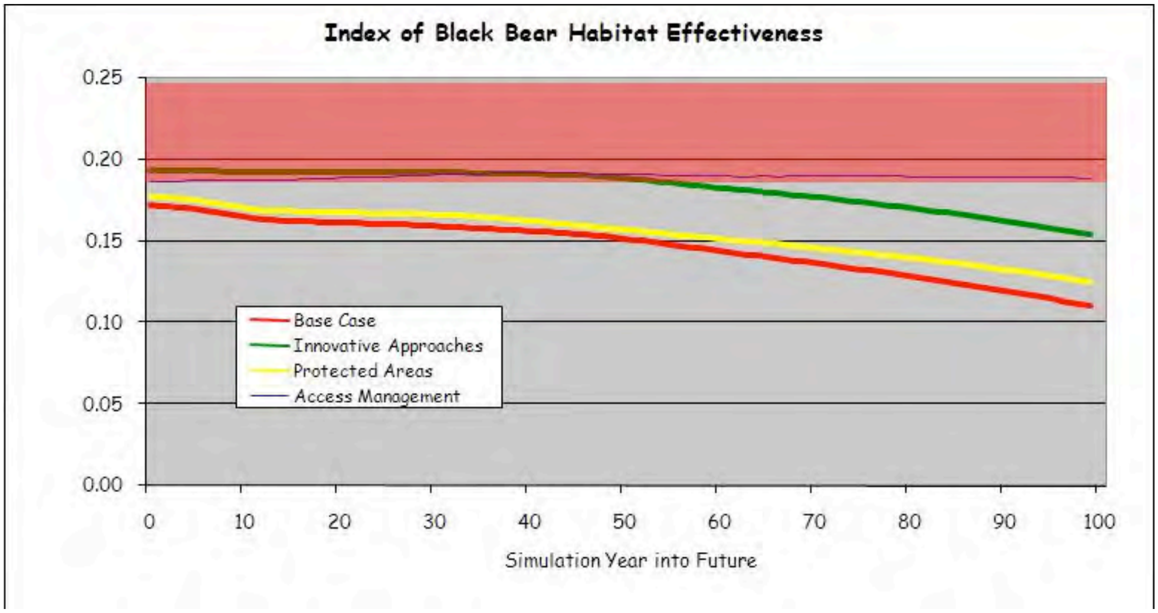


Figure 33: Forecasted Black Bear HEI performance in Main Program Modelling

Currently, the index is forecast to be approximately 11% below lower limit of NRV because of historical human activity levels, the effects of linear features and hunting.

Access management is identified as the management strategy having the most significant opportunity to mitigate future effects enabling the indicator to remain within the NRV. Innovative approaches does reduce risk significantly in the next 50 years and modelling suggests that in the long term it could mitigate the effects of future human activity by roughly 50% compared with the base case.

Sensitivity Analyses

Indicator performance was forecast at double bitumen production rates, double the reclamation time and both double bitumen production and double reclamation time to test the risk associated with these key modelling uncertainties.

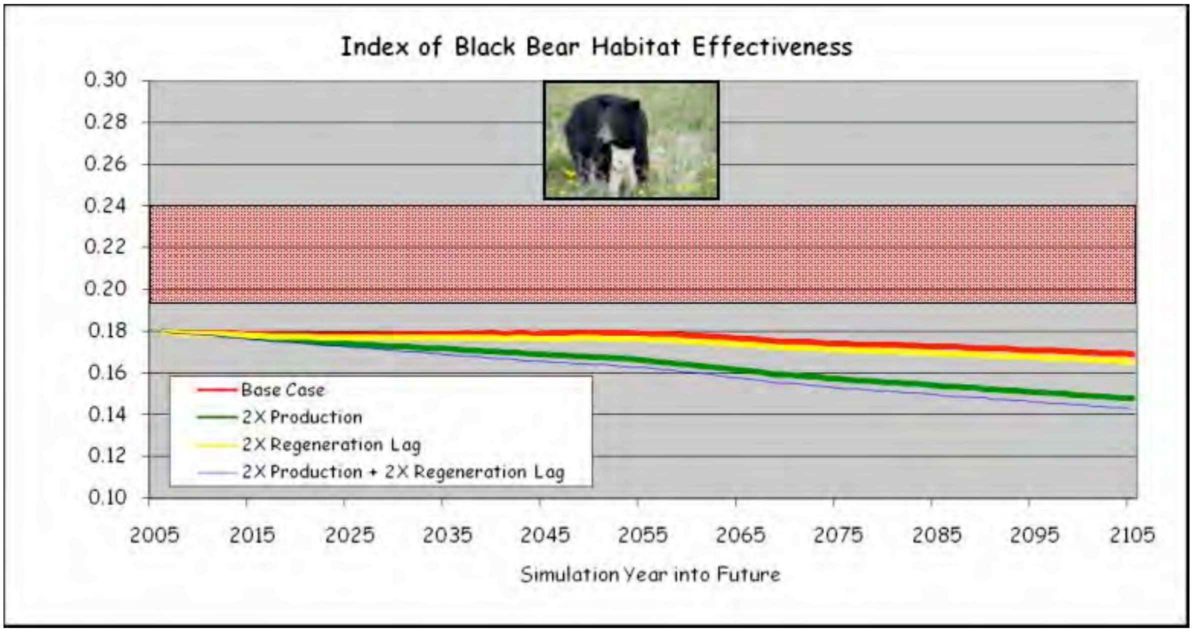


Figure 34: Forecasted Black Bear HEI performance in Sensitivity Modelling

Black Bear HEI is sensitive to bitumen production rate. This is most likely a consequence of the increased linear feature density spread across Black Bear habitat and increasing the likelyhood of human interaction. The index is slightly sensitive to delays in reclamation. When double reclamation period is combined with double bitumen production rates, forecasted indicator performance falls to approximately 74% below the lower limit of NRV over the planning horizon.

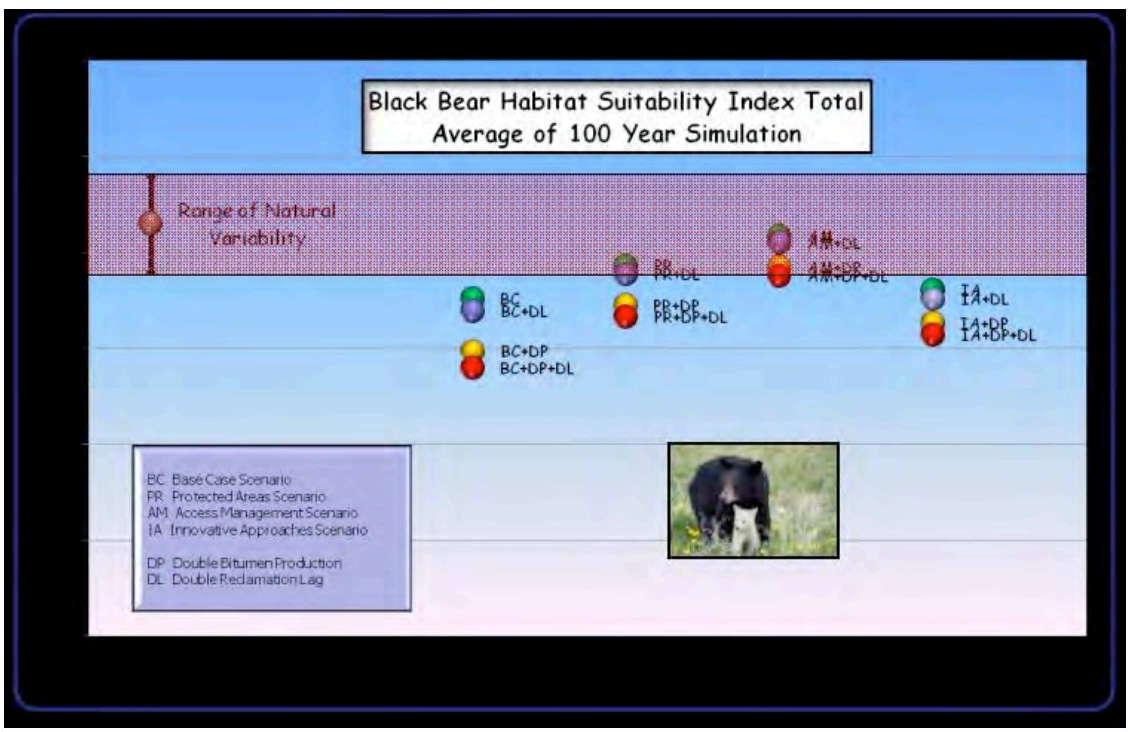


Figure 35: Comparison of Management Strategy effect on the average of Black Bear HEI forecasted performance over the 100 year planning horizon

The potential for access management to mitigate effects is demonstrated in the sensitivity analyses similar to what was learned in the Main Program Modelling. Overall, Access management can be a very powerful tool to mitigate development impacts and offsett risk associated with increased bitumen production and/or poor reclamation success.

5.6.7. Key Indicator Performance Drivers:

- Selective to Habitat Types
- Sensitive to Linear Features and Zone of Influence (ZOI)
- Sensitive to Stand Age (middle seral stages less desirable)
- Highly Sensitive to Human Density

5.6.8. Indicator Specific Monitoring Considerations

The Black Bear HEI requires 10 variable inputs as described below:

5.6.8.1. GIS Polygonal and Linear Feature Analysis

Area by Landscape Type, Footprint Type, and seral stage, road density and shrub density

5.6.8.2. Models and Assumptions

Habitat Quality of each Landscape Type and Footprint Type, Buffer Width for Zone of Influence, forest structure value

5.6.8.3. Government Agency Captured Information

Human density (# people/km^2)

5.6.8.4. Level of Integration from ABMI:

5.6.8.4.1. Habitat: Moderate

The current 20 km systematic grid design used by ABMI is expected to to effectively track changes in regional black bear habitat in an unbiased manner by detecting changes in habitat quantity and quality as well as human footprint. In 2008, the ABMI is expected to be able to identify the number of sample sites that will be needed to detect a significant change in black bearhabitat.

http://www.abmi.ca/abmi/reports/reports.jsp?categoryId=0

5.6.9. Other Identified Organizations:

5.6.9.1. Agency: Alberta Fish and Wildlife

Activities: AFW manages black bears as a game species, setting quotas for allowable hunts based on trend information.

http://www.srd.gov.ab.ca/fishwildlife/livingwith/huntingalberta/default.aspx

5.6.9.2. Agency: University of Alberta, Mark Boyce Lab

Activities: Under Mark, Sophie Czetwertynski is pursuing her Ph.D. thesis on this project with the study being conducted on the Cold Lake Air Weapons Range and adjacent lands within the Alberta Pacific Forest Management Area. There are many unknowns about black bear hunting and its consequences for harvest management. For example, early work by Gerry Kemp in Alberta suggested that because adult males are known to kill cubs, harvesting males would reduce infanticide and enhance production of young bear. The story is almost certainly more complex, and it is not clear that an old male that has tended females within his home range will kill his own cubs, but if he were removed, replacement bears would be expected to kill cubs sired by another male. This research is aimed as answering some of these questions.

http://www.biology.ualberta.ca/faculty/mark_boyce/?Page=719

Agency: Alberta Professional Outfitters Society (APOS)
Activities: Bear harvest; contribute to management and fund some research.

http://www.apos.ab.ca/

5.6.10. Identified scientific knowledge gaps:

- Spatial distribution of populations
- Wildlife Movement Corridors

5.7. Indicator: Old Forest

5.7.1. Indicator Category: Environmental

5.7.2. Goal: Sustain the natural range of vegetation communities, successional patterns and ecological processes.

5.7.3. Modelled Condition - Green

The indicator is currently projected to be within NRV and modeling suggests that the indicator will remain above the regional objective for at least the next 30 years.

5.7.4. Indicator Rationale:

The RMWB is dominated by boreal forest. Old forest is commonly invoked as an indicator of how well management strategies are sustaining the natural range of vegetation communities, successional patterns and ecological processes. Old forests also provide critical visual and thermal cover and complex structure for many wildlife species and as such are an important habitat component for many species. Finally, forest age is readily measurable using a variety of data sources and so data availability is generally good.

5.7.5. Indicator Natural Range of Variability:

The NRV was determined from 50 stochastic ALCES runs using a back-casted dataset and applying natural disturbance in the absence of anthropogenic influence. To some extent, the NRV is a product of current forest composition and age class and as such all of the stochastic run results originate at a common point – roughly 20% of the study are in an Old Forest condition. The range spans from 12% to 55% of the RMWB and is an acknowledgement that natural conditions are highly variable and that the index could be expected to fluctuate naturally within this range.

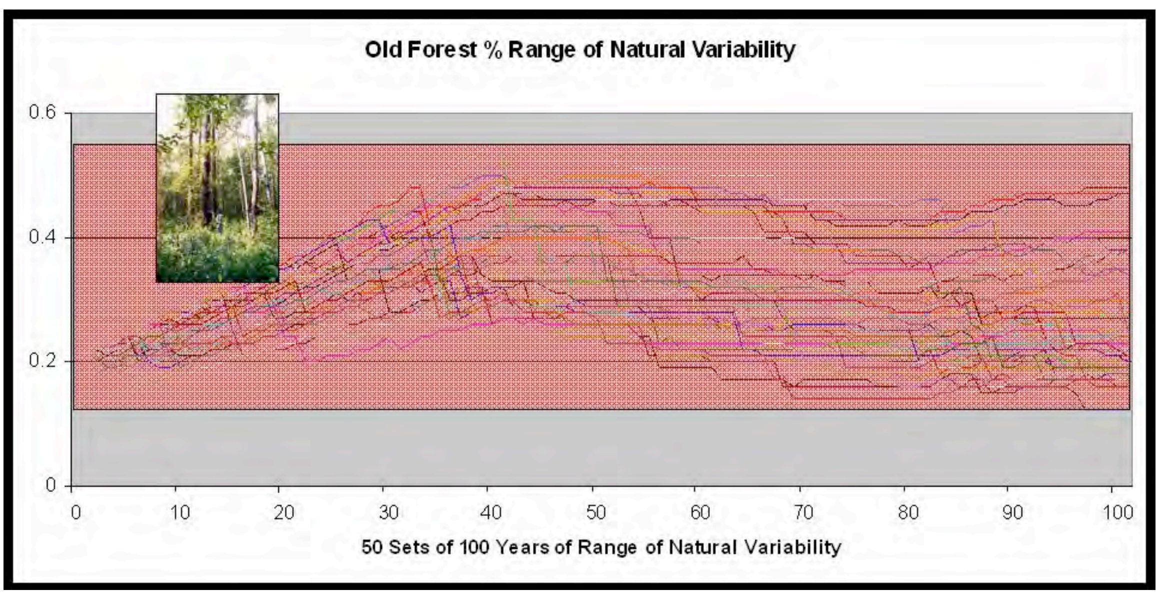


Figure 36: Old Forest Natural Range of Variability

5.7.6. Forecasted Scenario Outcomes for Old Forest:

The graph below shows the forecasted indicator performance with the NRV as a reference point. Scenarios forecast include the Base Case, Innovative Approaches, Protected Areas and Access Management.

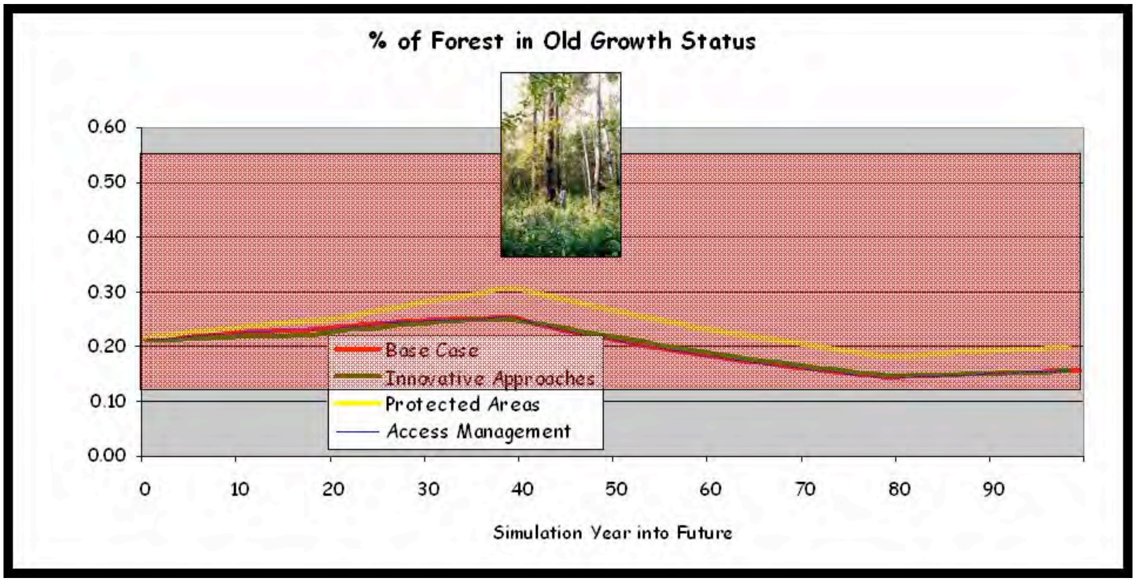


Figure 37: Forecasted % Old Forest performance in Main Program Modelling

Currently, the index is forecast to be within but at the lower limit of NRV. As mentioned, most of the RMWB is still undisturbed by man and so the initial condition is largely a result of natural disturbances. The primary natural disturbance agent influencing forest age is fire.

Fire rates were based upon an average 80-year fire cycle consistent with a SEWG commissioned study completed by Bandaloop Landscape-Ecosystem Services, *Natural Levels of Forest Age-Class Variability on the RSDS Landscape of Alberta*. (Available online at: www.cemaonline.ca). Stochastic modelling of this fire cycle within the RMWB landscape was completed using the natural disturbance module of ALCES® to compute an average burn area by landscape type by year for the projection. This burn rate was then deterministically applied within the ALCES® and spatial modelling scenarios. Between roughly 36,000 – 39,000 ha per year were simulated to burn naturally as shown in the figure below.

Map Now software which is designed for use with ALCES® was utilized to generate a plausible fire pattern representative of the fire simulated stochastically within ALCES®. A randomized algorithm identifed plausible burn patterns spatially over the study area and then chose the location to burn within each landscape type in each period until it reached the number of fire patches and area of fire required. The fire schedule was then rasterized and exported for overlay with the spatial resultant. An example of the resulting fire pattern in a 5-year period is shown in the figure to the right – fires are red.

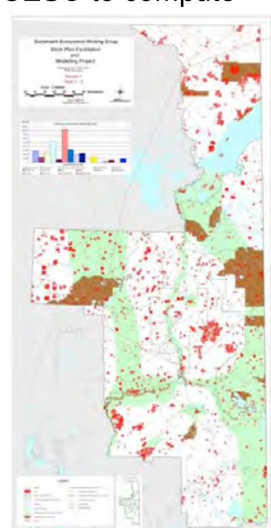


Figure 38: 5-year period spatial fire simulation

Currently old forests are well within NRV. The area of old forest is projected to increase during the next 3-4 decades (because of starting age class structure), and will then decline because of the additive effects of logging, fire, and energy sector reclamation.

With the caveat of a constant fire rate in mind, the forecasting suggests old forests will remain within RNV for all scenarios. Their prevalence will differ markedly from active and protected landbase. Establishment of expanded protected areas can increase the probability of old forests remaining within NRV for the entire planning horizon.

5.7.7. Sensitivity Analyses

Indicator performance was forecast at double bitumen production rates, double the reclamation time and both double bitumen production and double reclamation time to test the risk associated with these key modelling uncertainties.

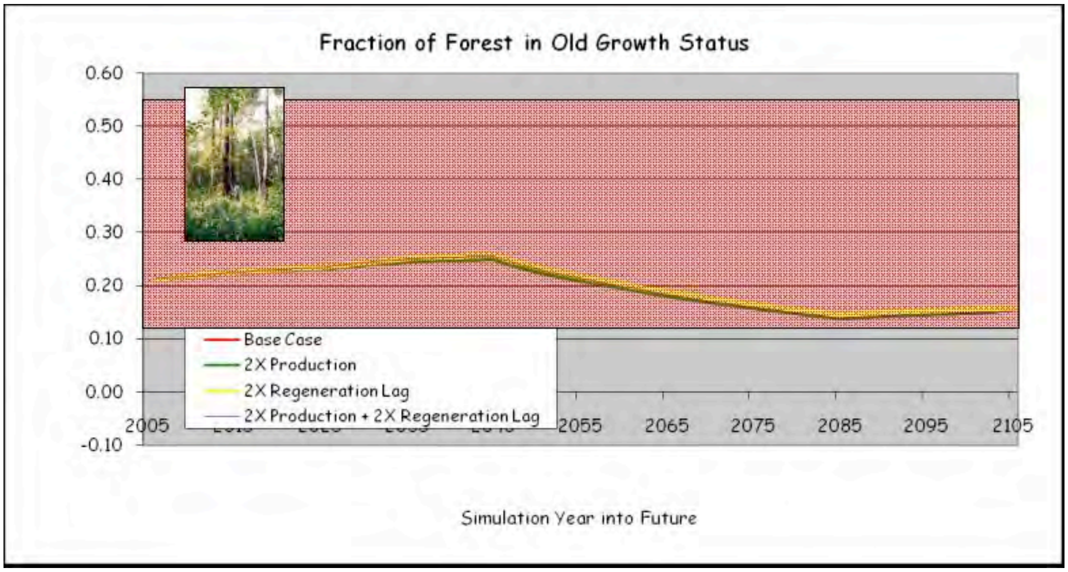


Figure 39: Forecasted Old Forest performance in Sensitivity Modelling

Old forest is insensitive to changes in bitumen extraction rates and reclamation largely because of the amount of old forest salvaged from operations is relatively low compared with the amount of old forest in the region.

5.7.8. Key Indicator Performance Drivers:

- Very sensitive to fire and logging
- Relatively insensitive to increased bitumen production and increased Reclamation lag

5.7.9. Indicator Specific Monitoring Considerations

5.7.9.1. GIS Polygonal and Linear Feature Analysis

Undertake a periodic update of the forest inventory for areas disturbed by fire, forestry or energy sector clearing.

5.7.9.2. Level of Integration from ABMI: Moderate

The ABMI is expected to be able to detect broad age class ranges for the region. Maintaining current forest inventories will be the most effective, which is not a direct component of the ABMI.

http://www.abmi.ca/abmi/reports/reports.jsp?categoryId=0

5.7.10. Other Identified Organizations:

5.7.10.1. Agency: Alberta Sustainable Resource Development

Activities: works to ensure forests remain vibrant in Alberta and uses timber permits, uses timber quotas and forest management agreements to manage the province's timber resources.

http://www.srd.gov.ab.ca/forests/managing/default.aspx

5.7.11. Identified scientific knowledge gaps:

Complete comprehensive and consistent inventories for the entire region of:

- Vegetation - there are significant shortfalls in forest inventory including large areas without reliable leading vegetation species and age.
- Footprint – a common, current source of active footprint was not available for this study

6. Selected Other Indicators Modelled During Development of the TEMF

Several other indicators were assessed during the development of the TEMF that are not included as management response triggers. Three of these are considered key trend indicators and are summarized here.

6.1. *Area of productive forest land and percentage of growing stock*

6.1.1. Indicator Category: Economic

6.1.2. Goal: Sustain a land base for timber harvest

6.1.3. Modelled Forecast

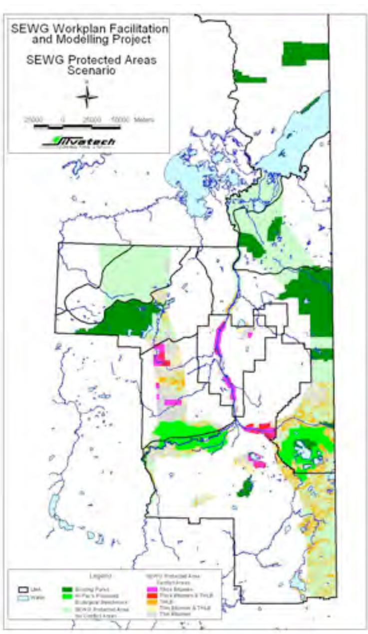
The area of productive forest land is forecast to decrease over the next 30 years and the magnitude of the drop is dependant upon the total volume of bitumen extracted and the timeliness of reclamation. Merchantable growing stocks decline over the next 50 years to a long-term sustainable level.

6.1.4. Indicator Rationale:

The RMWB is dominated by boreal forest and currently supports a vibrant forest industry. In order to ensure long-term sustainability of the commercial forest harvesting industry, the woodbasket supporting it must be maintained. Two key measures of woodbasket sustainability are the area of productive forest land and the amount of merchantable growing stock on that land base.

6.1.5. Forecasted Scenario Outcomes for Productive Forest Land and Merchantable Growing Stock:

The Base Case and Access Management scenarios have the same productive forest land base while the area in the Innovative Approaches is slightly larger as a result of less energy sector footprint that is reclaimed faster. However, the Protected Areas scenario has a significant impact on the area of productive forest land. The map below shows a spatial representation of where productive forest land was forecast to be reduced in the Protected Areas scenario (areas colored yellow, orange and red) – a 9% (318,000 ha.) reduction of productive forest land. The graph below shows the implications for merchantable growing stock.



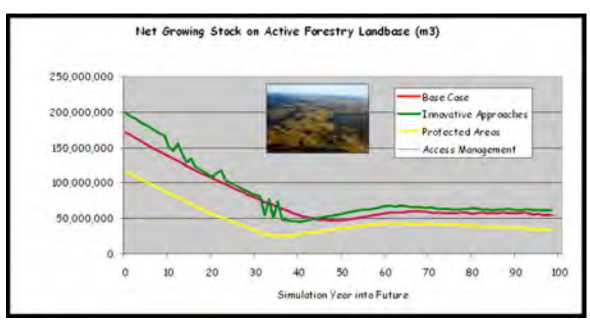


Figure 40: Productive Forest Land & Growing Stock

Over the next 35 years, merchantable growing stock is forecast to be approximately 40% lower than in Base Case because of the reduction in productive forest land. In the long term, the difference is reduced somewhat to about 30% as the age class distribution is normalized.

6.1.6. Sensitivity Analyses

Indicator performance was forecast at double bitumen production rates, double the reclamation time and both double bitumen production and double reclamation time to test the risk associated with these key modelling uncertainties.

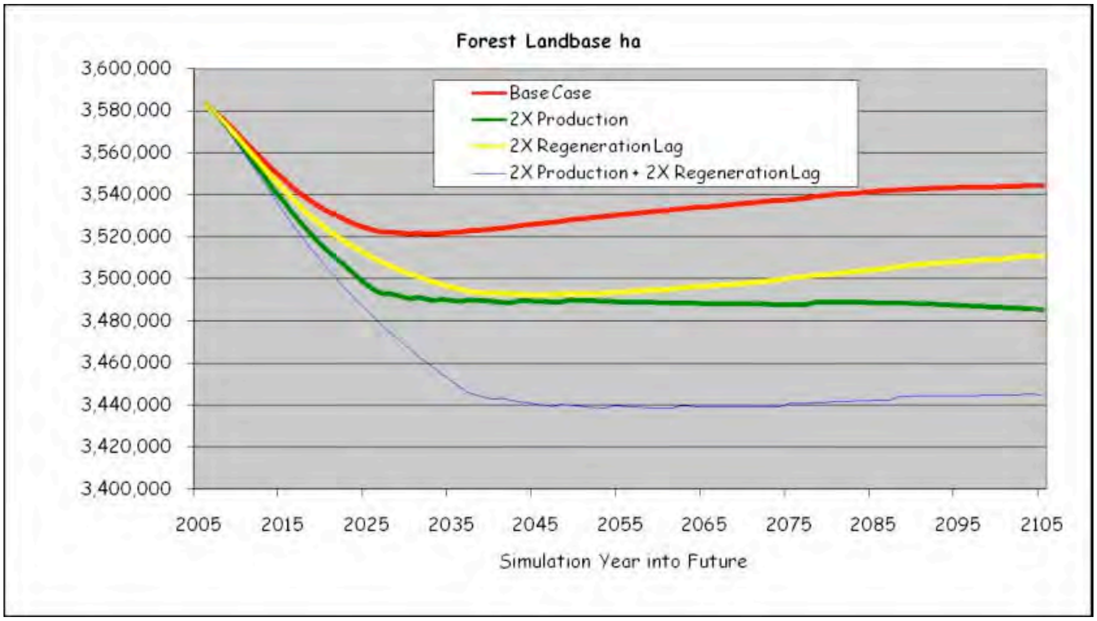


Figure 41: Productive Forest Land Area Sensitivity Analyses

Productive forest area is slightly sensitive to increasing production and increases in the reclamation lag. With more active footprint that persists longer, there is less productive forest area growing merchantable timber. However, the difference between Base Case and Double Production and Double Reclamation Lag is only 3%.

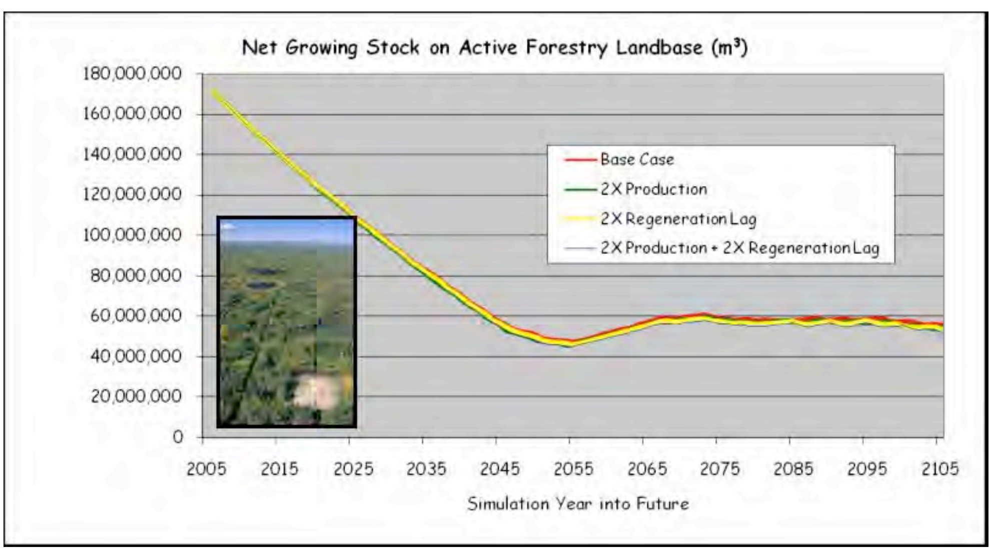


Figure 42: Merchantable Growing Stock Sensitivity Analyses

Similarly, with a very small reduction in productive forest land area there is a correspondingly insensitive response in merchantable growing stock.

6.1.7. Key Indicator Performance Drivers:

- Sensitive to productive land base withdrawals for other uses including Protected Areas
- Sensitive to fire and logging
- Relatively insensitive to increased bitumen production and increased Reclamation lag

6.1.8. Indicator Specific Monitoring Considerations

6.1.8.1. GIS Polygonal and Linear Feature Analysis

Undertake a periodic update of the forest inventory for areas disturbed by fire, forestry or energy sector clearing.

6.1.8.2. Level of Integration from ABMI: Moderate

The ABMI is expected to be able to detect broad age class ranges for the region. Maintaining current forest inventories will be the most effective, which is not a direct component of the ABMI.

http://www.abmi.ca/abmi/reports/reports.jsp?categoryId=0

6.1.9. Other Identified Organizations:

6.1.9.1. Agency: Alberta Sustainable Resource Development

Activities: works to ensure forests remain vibrant in Alberta and uses timber permits, uses timber quotas and forest management agreements to manage the province's timber resources.

http://www.srd.gov.ab.ca/forests/managing/default.aspx

6.1.9.2. Agency: Alberta Pacific Forest Industries Ltd.

Activities: Forest Management Agreement holder in the RMWB.

http://www.alpac.ca/

6.1.9.3. Agency: Northlands Forest Products Ltd.

Activities: Timber Quota holder in the RMWB.

http://members.shaw.ca/hewashko/

6.1.10. Identified scientific knowledge gaps:

Complete comprehensive and consistent inventories for the entire region of:

- Detailed timber supply implications for specific forest tenures if Protected Areas area expanded

6.2. Water Flow Dynamics (Discontinuity of Non-mainstem river systems)

6.2.1. Indicator Category: Environmental

6.2.2. Goal: Sustain natural watersheds and their elements

6.2.3. Modelled Forecast

The percent area of watersheds in a discontinuous or fragmented state primarily as a result of hanging culverts is projected to increase significantly over the next century.

6.2.4. Indicator Rationale:

Continuous watercourses are a critical ecological component of the RMWB and this is reflected in CEMA's TEMF Goal to Sustain natural watersheds and their elements. Anthropogenic access structures primarily in the form of roads typically require the installation of culverts to maintain drainage where they intersect streams and rivers. Lotic flow is determined primarily by inter-annual variation in precipitation or snow melt and there is an historical relationship between average annual precipitation and the probability of "hanging" culverts at these intersections caused by downstream plunge pool dynamics. Hanging culverts are of considerable concern to aquatic managers and ecologists since they interfere with the upstream movement of fish and other aquatic organisms.

6.2.5. Forecasted Scenario Outcomes for Water Flow Dynamics (Discontinuity of Non-mainstem river systems) :

The graph below shows the forecasted indicator performance with the NRV as a reference point. Scenarios forecast include the Base Case, Innovative Approaches, Protected Areas and Access Management.

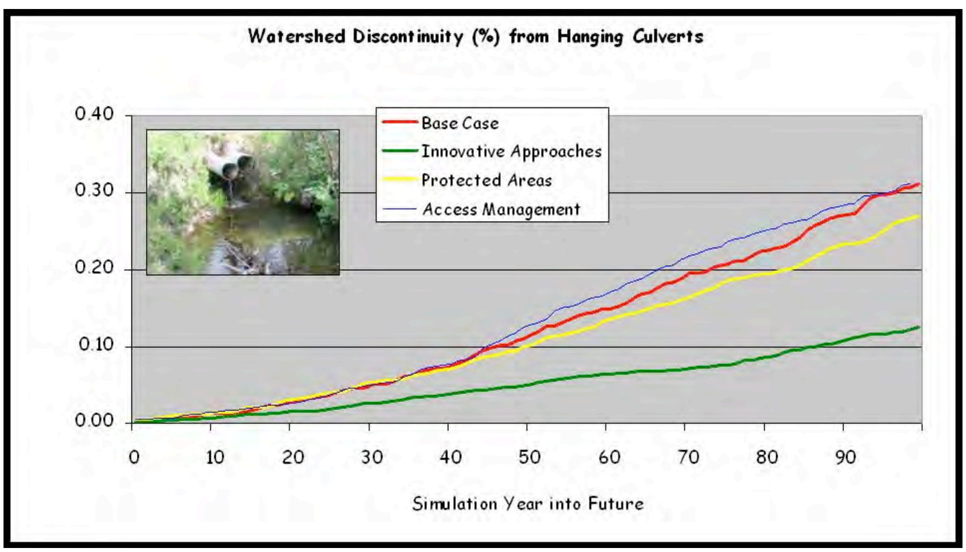


Figure 43: Watershed Discontinuity in Forecast Scenarios

Over the next 100 years, the percent area of watersheds becoming discontinuous as a result primarily of hanging culverts is forecast to increase in all scenarios. Base Case projections suggest a possible 30% increase. Innovative Approaches practices including the construction of bridges rather than culverts has the potential to significantly mitigate road access impacts (18% less) on watershed continuity.

6.2.6. Sensitivity Analyses

Indicator performance was forecast at double bitumen production rates, double the reclamation time and both double bitumen production and double reclamation time to test the risk associated with these key modelling uncertainties.

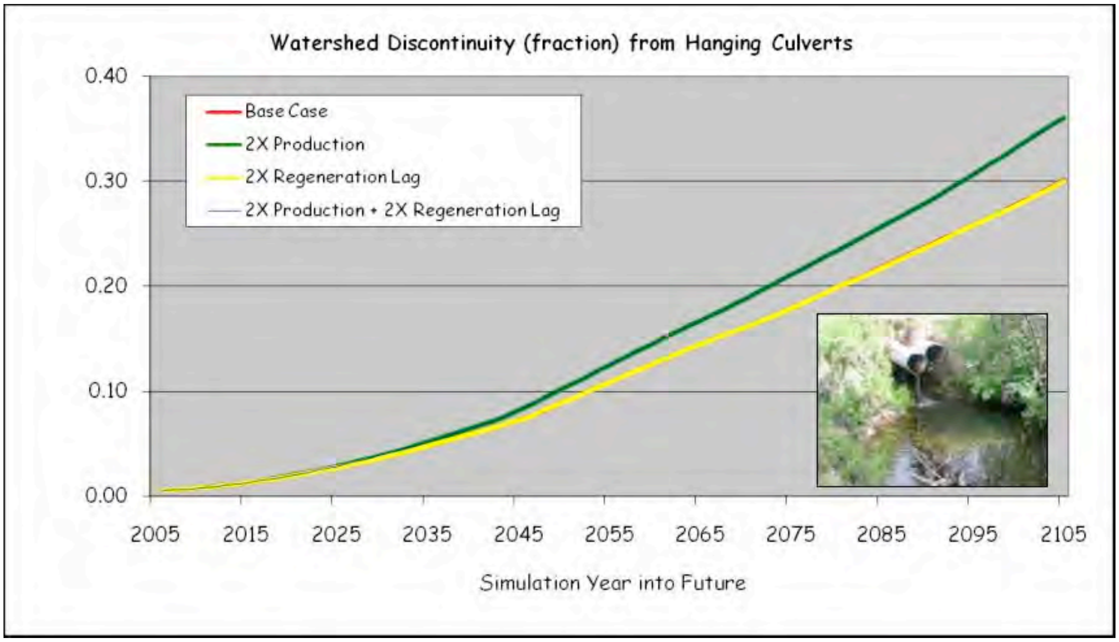


Figure 44: Watershed Discontinuity Sensitivity Analyses

Indicator performance is shown to be sensitive to increases in bitumen production, primarily because of the increase in road construction to access bitumen that require stream and river crossings.

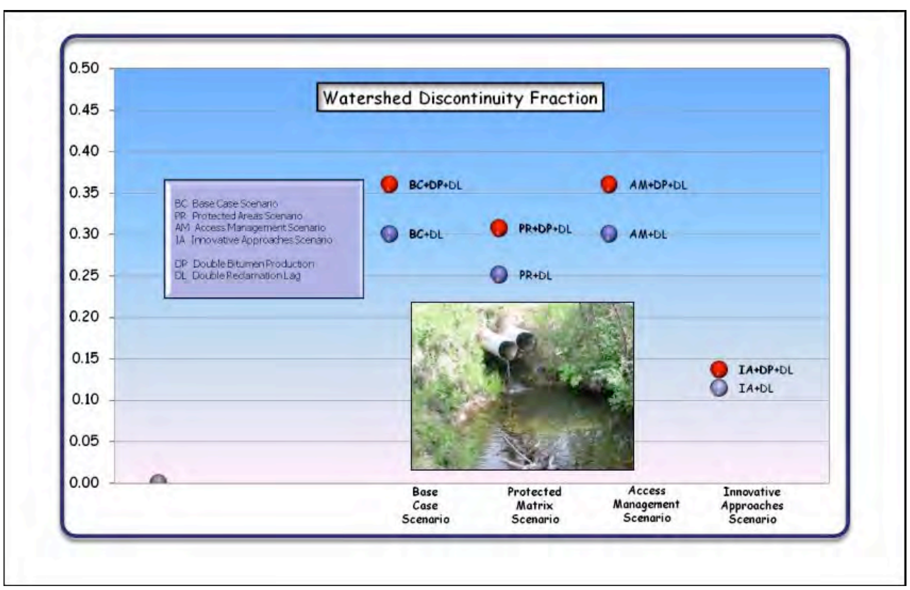


Figure 45: Comparison of Management Strategy effect on the average of Watershed Discontinuity forecasted performance over the 100-year planning horizon

Expanded protected areas mitigate impacts to some degree by reducing the area accessed by roads. However, given the nature of watercourses, and their connective nature across broad landscapes, it is Innovative Approaches that demonstrates the greatest potential to mitigate impacts from the Base Case scenario.

6.2.7. Key Indicator Performance Drivers:

- Sensitive to road density particularly related to bitumen production
- Sensitive to crossing types, particularly bridges vs culverts
- Relatively insensitive to increased Reclamation lag

6.2.8. Indicator Specific Monitoring Considerations

6.2.8.1. GIS Polygonal and Linear Feature Analysis

Undertake a periodic update of the linear access features and crossing structures associated with transportation networks primarily associated with forestry and energy sector activity.

6.2.8.2. Level of Integration from ABMI: Moderate

The ABMI can contribute to data collection for reporting on discontinuity at the regional scale by reporting on linear edge density and watercourse crossing density. In addition, ABMI protocols are consistent with ASRD protocols and therefore future collaborations are expected to contribute to finer resolution evaluations.

http://www.abmi.ca/abmi/reports/reports.jsp?categoryId=0

6.2.9. Other Identified Organizations:

6.2.9.1. Agency: Alberta Sustainable Resource Development

Activities: manages the development of road access infrastructure through integrated resource management on forest lands and responsible for access management through Forest Use Zones.

http://www.srd.gov.ab.ca/lands/managingpublicland/default.aspx

6.2.9.2. Agency: Department of Fisheries and Oceans

Activities: The Department is committed to ensuring safe, healthy, productive waters and aquatic ecosystems, for the benefit of present and future generations. It advances these goals by maintaining the highest possible standards of sustainable development, environmental stewardship and public safety.

http://www.dfo-mpo.gc.ca/home-accueil_e.htm

6.3. Density of linear features

6.3.1. Indicator Category: Environmental and Resource Use

6.3.2. Goal: Sustain natural watersheds and their elements and Sustain recreational capability and availability of wilderness opportunities

6.3.3. Modelled Forecast

Density of linear features in the RMWB is forecast to rapidly increase to approximately double current levels in the Base Case scenario within 20 years and then slowly decline through the mid- and long-term to roughly an 80% increase from today.

6.3.4. Indicator Rationale:

Density of linear features, also commonly referred to as "edge density" is well documented as a primary driver of ecological impacts on valued ecological components including within the RMWB. The importance of this indicator as a critical landscape element is evident in the TEMF ratified Goals and Indicators wherein density of linear features is the indicator of two separate goals. It is also a primary influencer of the performance of six of the seven Management Objective Indicators that can trigger a management response within the TEMF.

6.3.5. Forecasted Scenario Outcomes for Density of Linear Features :

The graph below shows the forecasted indicator performance with the NRV as a reference point. Scenarios forecast include the Base Case, Innovative Approaches, Protected Areas and Access Management.

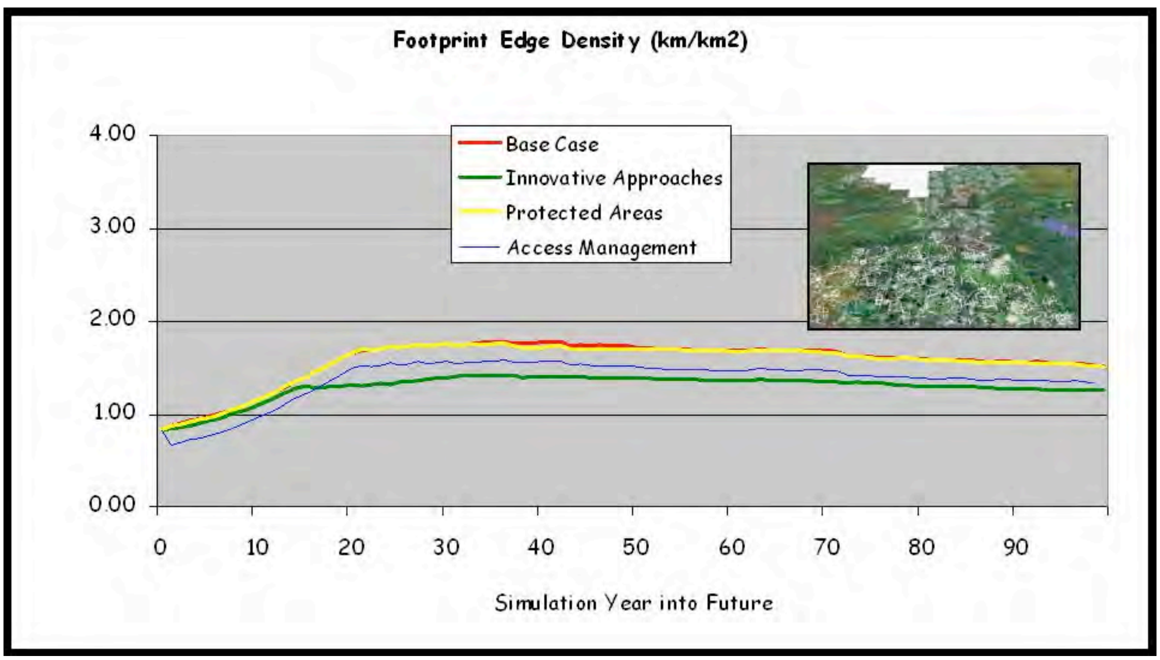


Figure 46: Density of Linear Features in Scenario Forecasts

Under the Base Case and Protected Areas scenarios, Density of linear features in the RMWB is forecast to rapidly increase to approximately double current levels in the Base Case scenario within 20 years and then slowly decline through the mid- and long-term to roughly an 80% increase from today. Since the Protected Areas scenario did not constraint bitumen production from the Base Case, the density of linear features is the same for both these scenarios. Access Management has the potential to mitigate impacts by roughly 10% whereas Innovative Approaches could mitigate impacts by as much as 30%.

6.3.6. Sensitivity Analyses

Indicator performance was forecast at double bitumen production rates, double the reclamation time and both double bitumen production and double reclamation time to test the risk associated with these key modelling uncertainties.

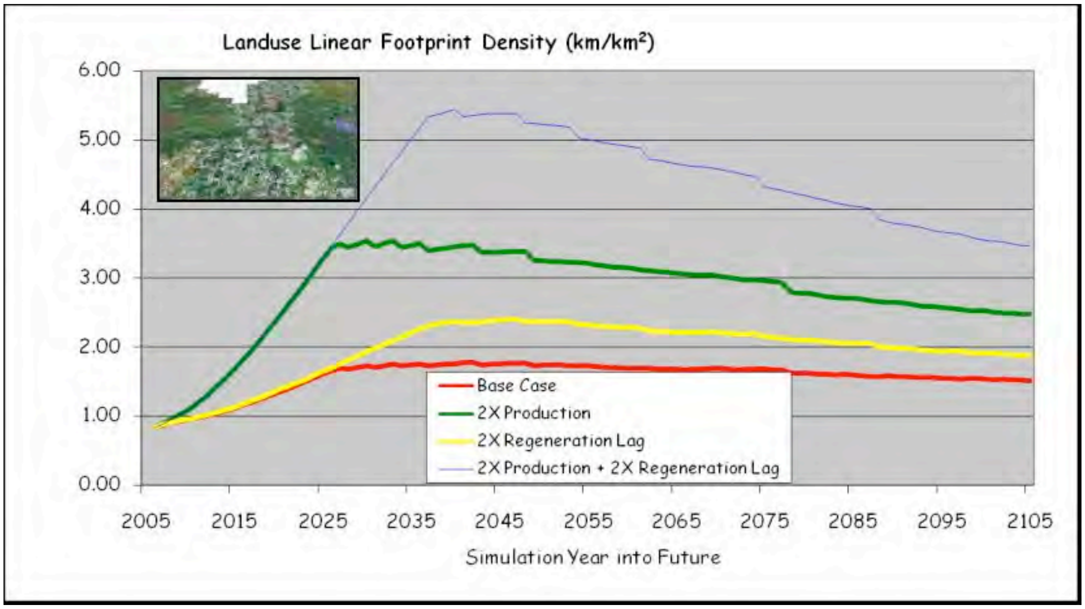


Figure 47: Density of Linear Features in Sensitivity Analyses

Indicator performance is very sensitive to increases in bitumen productionand reclamation lag. Linear edge density is extremely sensitive to both double production and double reclamation lag showing over a 5-fold increase within 35 years compared with the Base Case. Following are aerial photography samples of what three different levels of linear edge density could look like:

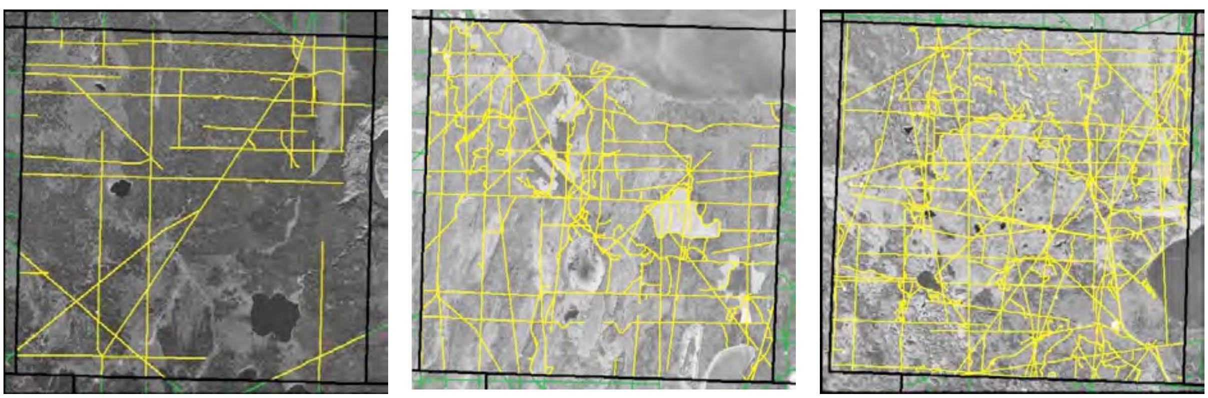


Figure 48: Examples of Linear Edge Density; 1.5, 3.0 and 4.0 km/km2

6.3.7. Key Indicator Performance Drivers:

- Very sensitive to in situ bitumen production

- Very sensitive to reclamation lag

6.3.8. Indicator Specific Monitoring Considerations

6.3.8.1. GIS Polygonal and Linear Feature Analysis

Undertake a periodic update of the linear features associated with energy and forestry sector activity.

6.3.8.2. Level of Integration from ABMI: High

The ABMI can effectively contribute to data collection for reporting on on linear edge density at the regional level although detailed assessments may be necessary to accurately assess the Intensive Zone.

http://www.abmi.ca/abmi/reports/reports.jsp?categoryId=0