Arsenic concentrations in wood, soil and plant tissue collected around trees treated with monosodium methanearsonate (MSMA) for bark beetle control

FINAL VERSION

Prepared for the British Columbia Ministry of Forests and Range

by

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Statement of Limitation

This report was prepared for the exclusive use of the British Columbia Ministry of Forests and Range (BC MFR) and may not be used by any other person or entity without the express written consent of the authors and BC MFR. The report, which specifically includes all tables and appendices, is based on data obtained from the analysis of samples by laboratories accredited by the Canadian Association for Laboratory Accreditation Inc. (CALA).

The content of this report is based on information collected during the author's analysis, their present understanding of the methods used, and their professional judgment in light of such information available. The report provides a professional opinion on the current standing of potential hazards to human health associated with total arsenic in surface soil, wood core, and foliage. This report does not offer legal guidance regarding compliance with applicable laws.

The services performed as described herein were conducted in a manner consistent with the level of care and skill normally exercised by members of the scientific and engineering communities currently working under similar conditions.

The findings and conclusions are valid as of June 15, 2009. If any conditions become apparent that differ significantly from the authors' current understanding as presented in this report, it is requested that they be notified immediately so that they can reassess the conclusion provided herein.

Executive Summary

Monosodium methanearsonate (MSMA) has been applied to lodgepole pines (*Pinus contorta* var. *latifolia*) in the province of British Columbia to suppress mountain pine beetle infestations, and the public has expressed concerns about the potential risks that trees previously treated with MSMA pose to human health and the environment. The goal of this study was to quantify total arsenic concentrations in wood, vegetation and soil samples collected from sites in BC with MSMA-treated trees, and to compare these results with samples collected at similar sites with untreated trees to gain an understanding of the movement of arsenic from MSMA-treated trees to the surrounding environment.

Silvicon Services Inc. of Smithers, BC collected a total of 382 samples from the Nadina and Cascades Forest Districts in 2008 and 2009. Arsenic concentrations ranged from below analytical detection limits (nd) to 62 ppm in wood cores, from nd to 62 ppm in soil samples, and from nd to 0.9 ppm in foliage samples. Although arsenic was detected in most wood cores collected from MSMA-treated trees, concentrations in 95 % of adjacent soil samples were below both background (*i.e.* naturally occurring) and the 12 ppm guideline specified by the Canadian Council of Ministers of the Environment (CCME). Total soil arsenic exceeded guidelines in three samples in the Cascades Forest District. Study findings suggest that elevated soil arsenic concentrations are confined to small areas and may be the product of isolated point-source contamination, such as MSMA spillage during application. It appears that arsenic associated with MSMA application is largely confined to the individual treated trees and is not migrating into surrounding soil and vegetation.

By extrapolating soil arsenic results to all MSMA-treated trees in the province of British Columbia, the authors estimates that approximately 0.2 % of the total forested area treated with MSMA could potentially contain arsenic concentrations above the 12 ppm CCME guideline. In addition, models simulating the hypothetical amount of arsenic that could be released into the soil from MSMA-treated trees falling to the forest floor and decomposing *in-situ,* found that decomposition could

possibly lead to locally elevated soil arsenic in areas with organic-rich surface soils, but not at sites dominated by mineral soil.

Some arsenic compounds are known to induce both carcinogenic and non-carcinogenic endpoints in humans and both were considered in this study. Risk to adult and toddler receptors was calculated for practical (*i.e.* hiker, forestry worker) and worst-case (*i.e.* spending entire life on a site with MSMA-treated trees) exposure to MSMA-treated wood, impacted soils, and harvestable foodstuffs in British Columbia forests. Risks for exposure to MSMA were conservatively (*i.e.* worst case) calculated as exposure to inorganic arsenic species. Our results suggest that there is no risk posed to infrequent users of the site (*e.g.* a hiker) or forestry workers. We have found that risk to human health may occur in the unlikely event that foodstuffs (*i.e.* berries and mushrooms) are harvested directly below the dripline of MSMA-treated trees and through direct contact with the wood beneath the bark of treated trees. The BC Ministry of Forests and Range prohibits the harvesting, removal, milling, and/or burning of MSMA-treated trees (BC MFR 2007a) which will reduce direct contact with treated tress, however, we recommend that individuals also avoid collecting edible foods from within the dripline of MSMA-treated trees. Overall, we conclude that humans are not at risk in the forests of British Columbia as a result of the use of monosodium methanearsonate MSMA (in attempts) to control infestations of mountain pine beetle.

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List of Abbreviations

95 UCL	95 % upper confidence limit
As	arsenic
ATSDR	Agency for Toxic Substances and Disease Registry
ASU	Analytical Services Unit
BC MFR	British Columbia Ministry of Forests and Range
BC MOE	British Columbia Ministry of Environment
CCA	chromated copper arsenate
CCME	Canadian Council of Ministers of the Environment
cm^2	centimetre squared
CoPC	chemical of potential concern
CSF	cancer slope factor
DBH	diameter at breast height (measured at 1.37 m)
DDW	distilled deionized water
DMAA	dimethylarsinic acid
EDI	estimated daily intake
ESG	Environmental Sciences Group
g	grams
$g/cm^{2}*d$	grams per centimetre squared per day
ha	hectare
HC	Health Canada
HG-AAS	hydride generation-atomic absorption spectrometry
HQ	hazard quotient

List of Abbreviations, cont'd

ICP-AES	inductively coupled plasma atomic emission spectrometer
ILCR	incremental lifetime cancer risk
kg/m^3	kilograms per cubic metre
LADD	lifetime average daily dose
m^3	cubic metre
mg/kg	milligrams per kilogram (equivalent to ppm)
mg/kg-d	milligrams per kilogram per day
MMAA	monomethylarsonic acid
MSMA	monosodium methanearsonate, the sodium salt of MMAA
nd	below analytical detection limit
ppm	parts per million (equivalent to mg/kg)
QA/QC	quality control/quality assurance
RAF	relative absorption factor
RSD	relative standard deviation
SRM	standard reference material
SQG	soil quality guideline
TDI	tolerable daily intake
TRV	toxicity reference value
TSA	timber supply area
US EPA	United States Environmental Protection Agency

1.0 Introduction

The contemporary outbreak of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) in British Columbia (BC) is estimated to be the largest insect epidemic recorded in North American history (Nelson *et al*., 2006). The beetle outbreak began in the mid-1990s and the BC Ministry of Forests and Range (MFR) (2006) estimates that by 2005 more than 8.7 million hectares of pine (*Pinus* spp.) forest were affected. At the current rate of spread, mountain pine beetle will affect 78% of the mature BC pine forest by 2018 (Walton *et al.* 2008).

A number of techniques have been used to suppress mountain pine beetle infestations, including the application of monosodium methanearsonate[1] (MSMA) or Glowon®, an organoarsenic herbicide (Morrissey *et al*., 2008). In the United States, widespread application of MSMA as an agricultural herbicide and defoliant began in the 1960s (US EPA, 2006). In Canada, MSMA was used solely by the forest industry to control small outbreaks of bark beetle at the brood stage, specifically mountain pine beetle and spruce beetle (*Dendroctonus rufipennis*) (Dost, 1995; BC MFR, 2007a). According to BC Ministry of Environment (BC MOE) records, a total of 8,669 kg of MSMA were applied in the province between 1987 and 2004, which translates to approximately 150,000 treated trees. Since 2005, the product's registration has expired and MSMA is no longer used in British Columbia.

The public has expressed concerns about the risks that MSMA is perceived to pose to human health and the environment. In 2007, the BC MFR published a policy document containing guidelines for the management of MSMA-treated or "legacy" trees[2] (BC MFR, 2007a). One objective of this policy was to initiate research that would investigate the impact of legacy trees on human and ecosystem health.

This report presents results from a sampling program intended to quantify total arsenic concentrations in wood, vegetation and soil samples collected from MSMA-treated tree sites and from similar reference sites that were not treated with MSMA.

[1]There is public inconsistency in the spelling of this compound. Monosodium methanearsonate is the scientifically correct name.

[2]Available at: http://www.for.gov.bc.ca/hfp/health/MSMA/108806%20Prov%20Policy.pdf

The results of a human health risk assessment are also presented. The authors reviewed the sampling program, analyzed and interpreted the data.

2.0 Background

2.1 British Columbia Mountain Pine Beetle Epidemic

The mountain pine beetle is native to British Columbia, and spends most of its life under the bark of pine trees, including lodgepole (*Pinus contorta* var. *latifolia*), ponderosa (*Pinus ponderosa*) and western white pine (*Pinus monticola*). Adult mountain pine beetles typically have a one-year life cycle, attacking live pines in mid- to late July or early August, constructing galleries under the bark of the tree and laying eggs. Over the winter, these eggs mature into larvae that emerge as adults the following summer (BC MFR, 1995; Morrissey *et al*., 2007). Under normal conditions, mountain pine beetles play an important role in forest health by attacking and killing old or weakened trees (NRC, 2006). The present-day epidemic-level populations are attributable to two main factors: an increase in the number of ideal host trees, and the persistence of weather favourable to mountain pine beetle survival at both the adult and larval stage.

Mature (>80 years) lodgepole pine (*Pinus contorta* var. *latifolia*) is the host species preferred by mountain pine beetle, because younger pines are better able to resist beetle attacks. Estimates suggest that mature stands of lodgepole pine are three times more abundant today than in 1910, largely due to fire suppression programs. Natural forest fires destroy mature forest, allowing a new stand of lodgepole to grow where the old one existed. Fire suppression stops this natural cycle, allowing lodgepole pines to live longer than normal (NRC, 2006). In addition, previous mountain pine beetle outbreaks were terminated by wet summers and early, cold winters in which temperatures dropped to -30 ºC or below in November (Safranyik *et al*., 1974; Samman and Logan, 2000). The exceptionally hot, dry summers and mild winters that have persisted in central British Columbia in recent years have facilitated mountain pine beetle survival. Current populations are large enough that the resistance of young trees is now of little importance, since the numbers of attacking beetles can eventually overcome the resin defences of even the most vigorous trees (Shore and Safranyik,

2004). Although future wet summers and/or cold winters could increase beetle mortality, it is unlikely that favourable weather would result in the termination of the current beetle outbreak given the proportions of the epidemic (Eng *et al*., 2004).

Presently, the mountain pine beetle epidemic affects all forest regions within the province of British Columbia, although the Southern Interior forest region is most heavily affected (BC MFR, 2007b). Maps of the extent of the mountain pine beetle epidemic in British Columbia are available on-line at:

http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/

2.2 Application of MSMA to Control Mountain Pine Beetle Spread

Treatments to control mountain pine beetle infestation fall into two broad categories. “Indirect” or “preventative management” controls endeavour to increase stand vigour and thus resistance to infestation. “Direct” controls aim to reduce or eliminate the mountain pine beetle populations by killing beetles before they emerge (under the bark of trees), thus breaking the epidemic cycle, and returning populations to an endemic state (Nelson *et al*., 2006). Direct control tactics include single-tree treatments such as removal and processing, felling and burning, debarking, or the application of MSMA. Large groups of infested trees are usually treated by block harvesting and processing (Shore and Safranyik, 2004). Synthetic pheromone baits are often applied to individual trees or stands to attract and concentrate beetles prior to the above-mentioned direct treatment methods. These pheromones mimic those released by unmated female beetles which make the first attacks on trees, and use pheromones to attract males and other females until numbers are sufficient to overcome tree defences (Shore and Safranyik, 2004).

MSMA is an arsenic compound that is applied in aqueous solution to an infested tree within the first three or four weeks following an attack, while the tree is still alive (BC MFR, 1995). The normal concentration is 0.32 kg elemental arsenic per litre of water and additives (see section 2.3 for more information on the chemical composition

of MSMA). A horizontal frill that just penetrates the outer rings of sapwood is cut with an axe at the base of the tree, and the MSMA solution is applied in the frill at a rate of 1 mL per 2.5 cm of tree circumference (Figure 2-1; HC, 2004a). The chemical is drawn up through the conductive tissue of the tree and kills both the tree and the beetles under the bark (Shore and Safranyik, 2004).

Advantages of the MSMA direct control method include: ease of equipment and material transport to sites, and ease of use in remote areas in which harvesting is not feasible. Application procedures for MSMA treatment of lodgepole pine infested with mountain pine beetle follow a series of discrete steps designed specifically to target the beetle and to minimize the impact to the surrounding environment (Morrissey *et al*., 2007). A disadvantage is the short time limit for application. MSMA must be applied within 24 days of initial beetle attack to be most effective (Nelson *et al*., 2006).

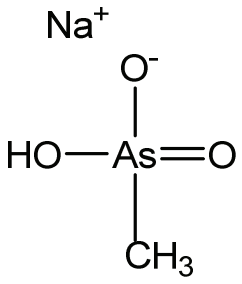


Figure 2-1. MSMA application to treat a beetle-infested tree in BC (photo care of BC MFR).

2.3 Chemical Composition of MSMA

Inorganic arsenic is widely distributed in nature, is found in soil and all organisms, and is released through natural processes such as the weathering of bedrock (Cullen and Reimer, 1989; Inskeep *et al.,* 2002). Arsenic is rarely found in its elemental state in nature; rather, it moves between various oxidation states (As(-III), As(0), As(III), and As(V)) and chemical species, and these transformations are governed by both biotic and abiotic processes (Oremland *et al.,* 2003).

MSMA is an organoarsenic compound which means that it possesses an arsenic-carbon (As-C) bond, and it has the chemical structure:



Although commercially synthesized from inorganic precursors for use as an herbicide, MSMA is also created through natural processes as part of the cycling of arsenic in the environment. At the pH of mammalian body fluids, the common parent acid monomethylarsonic acid (MMAA) is found in its ionized form (Dost, 1995).

Although there are many commercial formulations of MSMA, the only one used in Canadian forestry was sold under the name Glowon®. This formulation consisted of:

- water
- a polysaccharide gum
- 0.32 kg MSMA/L water
- pH adjusted to 5.6 with hydrochloric acid
- Cab-o-Sil™

- Tamol™, and
- A-14-N Fire Orange dye.

The polysaccharide gum was used to keep the herbicide in place following application by increasing the viscosity of the solution. Tamol™ was used as a wetting agent to lower the surface tension of water, making the Glowon® solution spread more easily during application and translocate more easily when absorbed by the tree. Tamol™ is similar to household detergents (*e.g.* those in shampoos and dish soaps). Cab-o-Sil™ was used as a suspending agent to keep the MSMA evenly distributed throughout the solution. Orange dye was added to indicate treated sites and to show applicators the quality of their work practices (Dost, 1995). Because MSMA is synthesized from inorganic precursors, traces of inorganic arsenic may be present in the solution as well (Manville *et al.,* 1988).

3.0 Methods

3.1 Field Sampling Methodology

Field sampling was conducted between Sept. 11 and Sept. 29, 2008, by Silvicon Services Inc. of Smithers, BC, at 20 sites in the Nadina and Cascades Forest Districts (10 sites in each district; Figure 3-1 to Figure 3-3, Appendix B). An additional sampling trip was undertaken by BC MFR personnel in early February, 2009.

3.1.1 Site Selection

All sites were located within the Cascades Interior Douglas Fir, dry cool (IDF dk) and Nadina Sub-boreal Spruce, dry cool (SBS dk) biogeoclimatic ecosystem classification subzones. Sampling sites were selected to capture a range of ecosystem variability, to target areas that had some of the most extensive use of MSMA, and to capture a cross-section of treatment dates. Sites selected also satisfied the following criteria:

- they were accessible by vehicle (*i.e.* no need for helicopter access) and within a reasonable distance (1-2 km) of roads, thus representative of sites most easily accessed by the public;
- they contained a minimum of five treated lodgepole pines and a minimum of five non-treated lodgepole pines; and
- if possible, they contained plants growing in proximity of both treated and untreated trees.

3.1.2 Sample Collection

At each site, three MSMA-treated and two untreated lodgepole pines of similar diameter were selected for sampling (Table 3.1). Only treated trees that were a minimum of 5 m apart, and untreated trees that were a minimum of 25 m from those treated, were chosen. An effort was made to select treated trees of the same decay state (*i.e.* old grey phase). Each sample tree was marked with paint and the year of treatment, site GPS co-ordinates, tree diameters, and percent woodpecker damage were recorded.

Table 3.1. Summary of the number of samples collected from each tree and region.

Sample type	Number of samples per tree		Number of samples per region		Total samples collected
	Treated	Untreated	Nadina	Cascades	
Wood core	1	1	50	50	**100**
Soil	2	1	80	95	**175**
Foliage	2	1	88	19	**107**
Total	**5**	**3**	**218**	**164**	

*Silvicon Services Inc. did attempt to collect berries at all visited sites, however, none were found at any of the sample locations.

On the north, east, south and west sides of each tree, the outer bark was removed and a core was collected at breast height (1.37 m) using a 5.15-mm diameter increment corer. The outer 2-4 cm of each core (not including bark diameter) was cut using a razor, and all four samples were deposited into the same labelled Ziploc® bag, resulting in a composite sample with a minimum weight of 15 g.

For each treated tree, one soil sample was collected near the drip line of the tree (the outer circumference of the tree branches where rain is shed to the ground), and another was collected 1-2 m from the drip line (away from the tree) using standard soil sampling methodology. Needles tend to accumulate below the drip line when they fall to the forest floor. Soil samples were collected below the drip line to capture MSMA that was translocated into tree foliage and subsequently deposited on the forest floor in needle litter (Norris *et al.,* 1983). For each untreated tree, one soil sample was collected near the drip line. To collect a sample, the duff[3] layer was removed to expose the humus layer and 300 g of soil were collected from the upper 10 cm of the soil profile. Care was taken to avoid rocks, roots or other debris. Soil was placed in labelled Ziploc bags and refrigerated.

Whenever possible, foliage samples were collected immediately adjacent to soil sample locations. A minimum of 30 g of foliage were collected from a single plant by cutting leaves with scissors at the petiole attachment point. Only intact leaves without signs of insect damage, fungal infection, or other injury were collected. Samples were placed in labelled Ziploc bags and refrigerated. Foliage samples were rinsed with distilled water the day of collection and dried. Scissors were decontaminated between samples using distilled water.

Additional samples were collected in February, 2009, from treated trees at two sites (J-11 and L-31) in the Cascades region that returned above-normal soil arsenic concentrations from the first round of sampling. Seven soil samples were collected around the drip line of tree J-11-1, and one was collected 1 m outside of the drip line. Four soil samples were collected around the drip line of tree L-31-3, one at a depth of 15 cm below the initial sample location, and two 50 and 100 cm downgradient of the initial sample location, respectively. One foliage sample was collected adjacent to the initial soil sampling location.

[3]Duff = forest soil layer of partially decomposed organic material.

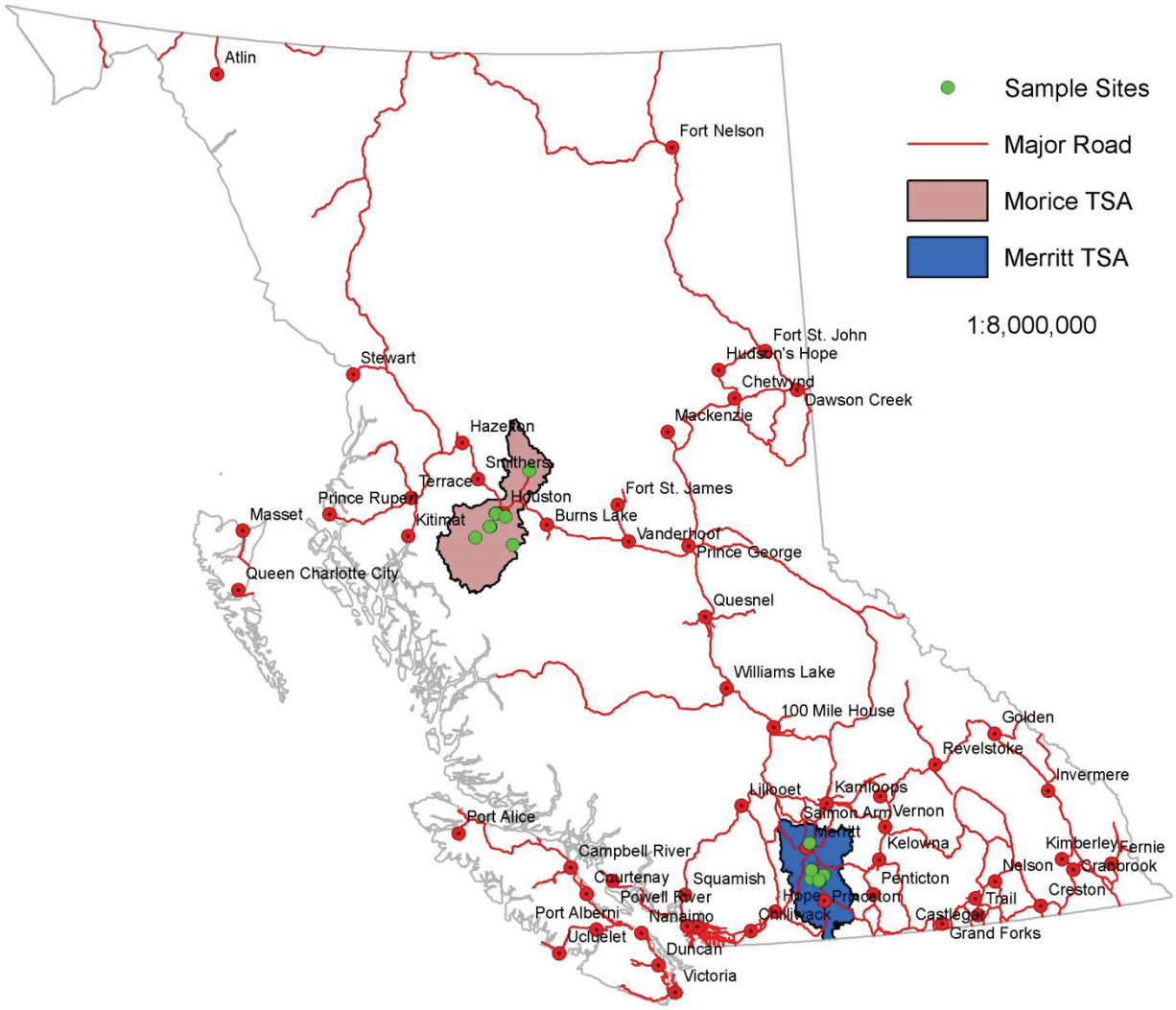


Figure 3-1. Provincial overview of sample sites in MSMA-treated areas in the Nadina and Cascades Forest Districts (Morice and Merritt timber supply areas (TSAs) respectively).

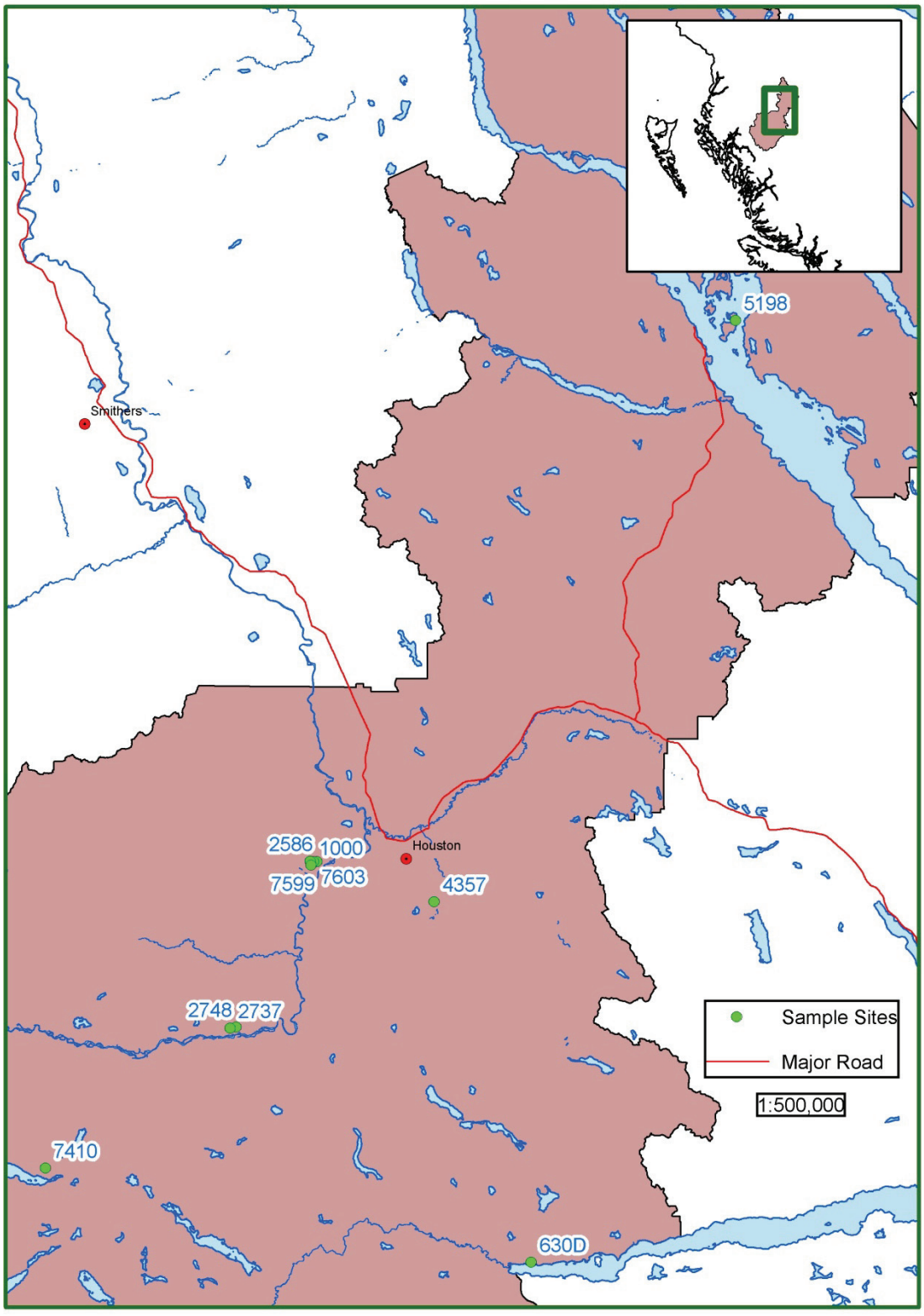


Figure 3-2. Sample sites in MSMA-treated areas in the Nadina Forest District (Morice TSA).

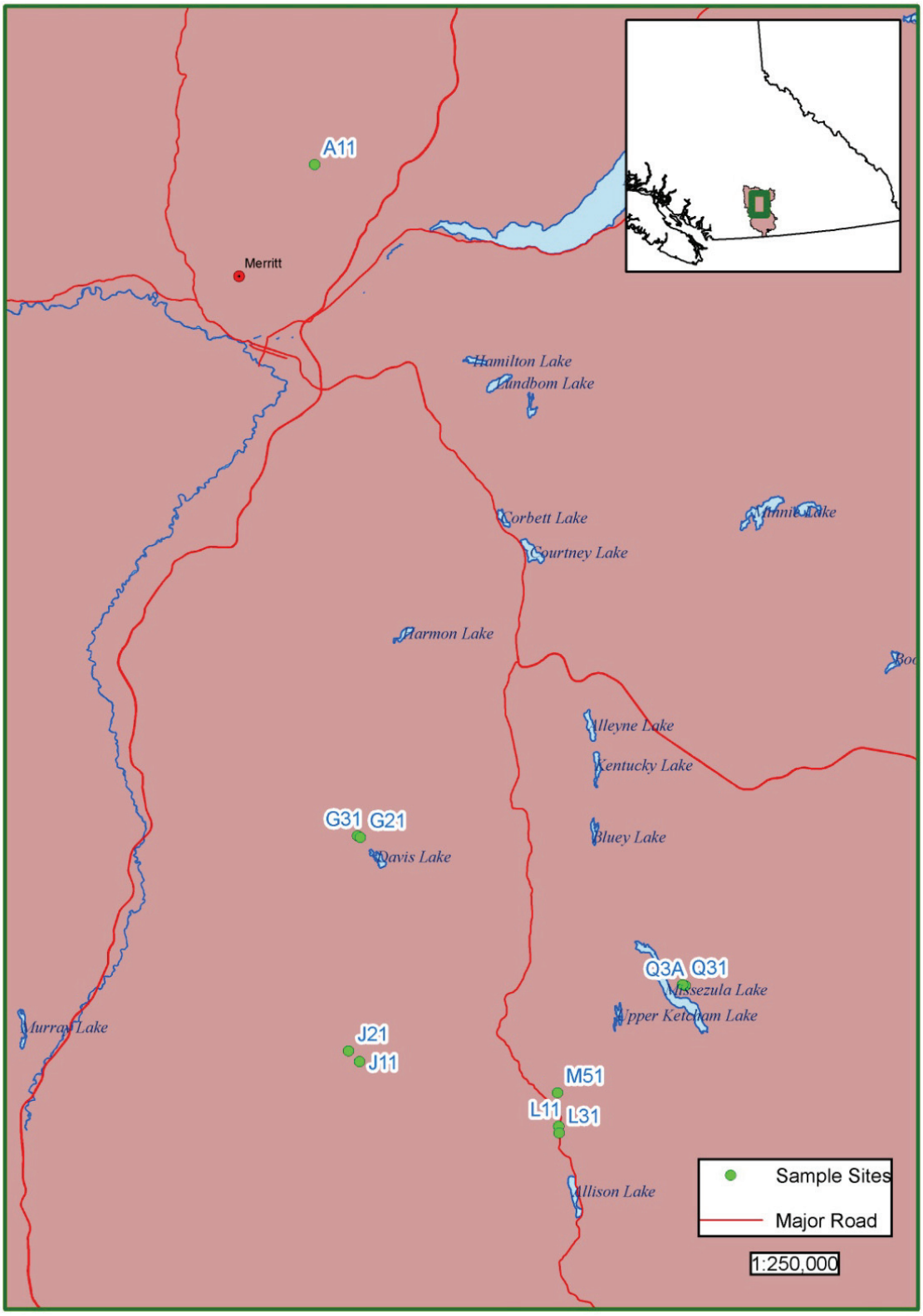


Figure 3-3. Sample sites in MSMA-treated areas in the Cascades Forest District (Merritt TSA).

3.2 Analytical Methodology

All samples were shipped to Kingston, ON, where they were analyzed for total arsenic at the Analytical Services Unit (ASU), Queen's University. Each sample was clearly labelled with a new, sequential, numerical code before being submitted to ASU. These codes masked any information concerning site location, sample type or possible arsenic concentration. Samples were stored in a secured area (before and after analysis) at a temperature appropriate for the analytical method.

3.2.1 Digestion of Sample Matrices for Arsenic Analysis

Soil

All 175 soil samples collected were air-dried and ground to a fine powder with a mortar and pestle. Stones were removed, as they would not be expected to contain any anthropogenic environmental contaminants. Approximately 0.5 g of powdered sample were heated with 2 mL of nitric acid and 6 mL of hydrochloric acid overnight so that the volume was reduced to 1-2 mL. This solution was then made up to 25 mL with distilled deionized water (DDW). Although not all the arsenic may be brought into solution by this procedure (some may be locked into silicate minerals), the arsenic that is released is considered to be of greater environmental significance.

Wood Cores and Foliage

Each of the 100 wood core and 107 vegetation samples collected was dried overnight in a low-temperature (25 °C) oven and a 0.5 g (± 0.0001 g) portion of the dried sample was weighed into a clean, dry Vycor® crucible, which was then placed in a Fisher Scientific ISOTEMP programmable muffle furnace. The furnace was programmed to ash the samples with the following heating regime: 1) 150 °C for 20 minutes; 2) 250 °C for 60 minutes; 3) 500 °C for three hours; and 4) room temperature until the next morning. The ashed samples were removed from the furnace the next day. A few drops of 18 MW DDW were added to wet the ash, followed by the addition of nitric (HNO_3) and hydrochloric (HCl) acids to digest the ashed sample. Following the

acid digestion, hydrogen peroxide (H_2O_2) was added to the samples and the volume was reduced to 1 mL. The samples were then made up to 12.5 mL with 18 MW DDW. All reagents used were reagent grade.

Samples were digested in batches of up to 36, which comprised up to 28 samples, two blanks, four duplicates and two samples of standard reference material (SRM). The SRMs for soil were MESS-3 (a sediment from National Research Council Canada) and SS-2 (a soil from SCP Science), and for wood cores and foliage were Bush Branches and Leaves (GBW-07603, from the Institute of Geophysical and Geochemical Exploration, China) and spinach (NIST-1570A from the National Institute of Standards and Technology).

3.2.2 Analysis Technique

The analytical technique and instrumentation used for samples depended on the concentration level of the analyte of interest (arsenic); all samples were first analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) and samples that were below the detection limits of this technique were reanalyzed by hydride generation-atomic absorption spectrometry (HG-AAS). The digestion of samples prior to analysis, mineralized all forms of arsenic, and thus all samples were analyzed for total arsenic. Analysis of total arsenic measures MSMA, any inorganic residual from the manufacturing process, any modified forms of MSMA that were generated following application, as well as any naturally occurring arsenicals, but does not differentiate these forms.

Arsenic by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES)

All samples were measured using a Varian Vista AX ICP-AES. Soil extracts were diluted using 2 % nitric acid, and all sample extracts were filtered through a Whatman No. 40 filter paper prior to analysis. A three-point calibration was run with each half batch as well as a calibration check sample from a separate source. The arsenic concentration was calculated in mg/kg (ppm) for soil, wood core and foliage samples.

Arsenic by Hydride Generation-Atomic Absorption Spectrometry (HG-AAS)

Samples that were below the detection limit of the ICP-AES procedure were reanalyzed by HG-AAS, using an Instrumentation Laboratories AA spectrometer, as gaseous arsenic hydride, after reaction of arsenic in the sample with sodium borohydride in a hydride generator. The determination was carried out using a continuous-flow hydride generator in which a stream of the analyte solution was mixed with streams of borohydride and acid reagents. Digested samples were prepared for analysis by diluting them tenfold and then combining them with hydrochloric acid, potassium iodide and hydroxylamine hydrochloride. The lamp wavelength was set at 197.2 nm and an air-acetylene flame was used. A five-point calibration was run with each half batch as well as a calibration check sample from a separate source. The arsenic concentration was calculated in mg/kg (ppm) for soil, wood core and foliage samples.

3.3 Quality Assurance/Quality Control

An internal quality assurance/quality control (QA/QC) program was implemented to allow the monitoring of data quality on an ongoing basis. Accuracy was measured and controlled by instrument calibration, the use of SRMs and calibration checks, and the analysis of blanks. Precision was measured and controlled by the analysis of analytical duplicates, which are replicate preparations and analyses of the same sample. Comparison of the average relative standard deviations (RSD%; also known as coefficient of variation), which are calculated as the standard deviation divided by the mean, were used to quantitatively evaluate laboratory precision.

Blank and SRM samples were prepared at a frequency of one for every 14 samples; duplicates were prepared at a frequency of one for every 7 samples. Analytical blanks were processed through extraction/digestion and analysis procedures. These blanks give a measure of the quantity of any contaminant (analyte) that may be added to the overall result during the analysis. SRMs are samples with known certified concentrations (*e.g.* soil reference material MESS-3) for which the laboratory has established control limits, and results are compared with the control limits. The results of

the QA/QC program are presented in Appendix A. All data discussed in the body of this document are reported to two significant figures.

4.0 Results and Discussion

4.1 Arsenic Concentrations in Wood Cores, Soil and Plant Tissue

The following section summarizes total arsenic concentrations in 382 samples collected from the Nadina and Cascades Forest Districts in 2008 and 2009. Complete sample results are presented in Appendix B.

4.1.1 Nadina Forest District

The average arsenic concentration in wood core samples (n = 30) collected from trees treated with MSMA in the Nadina district was 10 parts per million (ppm), with concentrations ranging from below analytical detection limits (nd) in tree 7603-3 to 55 ppm in tree 7603-2 (Table 4.1). Average arsenic for cores from untreated trees (n = 20) was nd and the maximum concentration was 0.5 ppm in tree 7603-5.

Average arsenic in soil samples (n = 30) collected below the canopy drip line of MSMA treated trees was 5.0 ppm, with concentrations ranging from 2.2 ppm (sample 2737-2-D) to 10 ppm (sample 5198-1-D). For foliage samples collected in the same area (n = 33), the average arsenic concentration was 0.2 ppm, with concentrations ranging from nd (multiple samples) to 0.9 ppm (sample 7603-2-D). Average arsenic for soils collected 1 m outside of the drip line of treated trees (n = 30) was 4.6 ppm, with concentrations ranging from 1.8 ppm (sample 630D-1-F) to 9.8 ppm (sample 5198-2-F), while arsenic concentrations for all adjacent foliage samples (n = 33) were nd. Soil samples collected beneath the drip line of untreated trees (n = 20) had an average arsenic concentration of 3.3 ppm, and concentrations ranged from 1.2 ppm (sample 630D-5-D) to 7.1 ppm (sample 7410-4-D). All foliage samples collected around untreated trees (n = 22) were nd.

Although no environmental quality guidelines exist to assess acceptable arsenic concentrations for plant tissue, there are guidelines for arsenic in soil (Table 4.2). For the Nadina region, arsenic concentrations in all soil samples collected around both MSMA-treated and untreated trees were below the Canadian Council of Ministers of the Environment (CCME) and BC Ministry of Environment (BC MOE) criteria of 12 and 20 ppm respectively for agricultural land use. In addition, arsenic concentrations for all soil samples were below the naturally occurring or "background" arsenic concentration of 15 ppm, which was determined by the BC MOE through analysis of soil samples from multiple sites across the region (BC MOE, 2005).

Foliage arsenic concentrations were only detectable in 18 % of the samples collected under the drip line of trees treated with MSMA in the Nadina Forest District. Least-squares regression analysis indicated that relationships between detectable arsenic in wood cores, and both drip-line soil (r^2 = -0.03, p = 0.6, n = 29) and foliage (r^2 = 0.04, p = 0.3, n = 10) were insignificant. This suggests that arsenic present in MSMA-treated trees sampled in the Nadina Forest District is not migrating into the surrounding soil and vegetation. In addition, there was no relationship between arsenic concentrations in wood cores and the year in which MSMA was applied (r^2 = 0.06, p = 0.1, n = 29).

4.1.2 Cascades Forest District

In the Cascades district, the average arsenic concentration in wood core samples (n = 30) collected from trees treated with MSMA was 14 ppm, with concentrations ranging from nd in multiple trees to 62 ppm in tree M-51-1 (Table 4.3). Average arsenic in cores collected from untreated trees (n = 20) was nd, and the maximum concentration was 1.5 ppm in tree J-21-4.

The average arsenic concentration for soil samples (n = 45) collected below the canopy drip line of MSMA treated trees was 4.8 ppm, with concentrations ranging from 0.4 ppm (sample L-31-3-D-a) to 62 ppm (sample L-31-3-D; Table 4.3). Arsenic in foliage collected from the same area (n = 8) was 0.3 ppm, with concentrations ranging from nd

(multiple samples) to 0.7 ppm (sample G--31-2D). For soils collected 1 m outside of the drip line of treated trees (n = 30), arsenic averaged 2.6 ppm, and concentrations ranged from 0.7 ppm (multiple samples) to 5.4 ppm (sample J-21-2-F), while arsenic levels in all adjacent foliage samples (n = 6) were nd. Soil samples collected beneath the drip line of untreated trees (n = 20) had an average arsenic concentration of 2.6 ppm, and levels ranged from nd (sample M-51-5-D) to 6.8 ppm (sample A-11-4-D). All foliage samples collected around untreated trees (n = 5) were nd for arsenic.

Arsenic concentrations in three soil samples collected below the drip line of MSMA-treated trees were above the background concentration of 25 ppm for the Cascades region (BC MOE, 2005; Table 4.2). Based on analysis of six replicates of each sample, average arsenic concentrations for drip line soil samples L-31-3-D, J-11-1-D and Q-31A-2-D were 62, 30 and 24 ppm, respectively (Table 4.3). All three values exceed CCME criteria, as well as the BC MOE agricultural and residential criteria. Maximum soil arsenic concentrations were not associated with maximum arsenic concentrations in wood cores from adjacent trees.

Trees J-11-1 and L-31-3 were revisited to collect additional soil and foliage samples to further delineate the distribution of arsenic around these trees. Seven soil samples were collected below the drip line of tree J-11-1 and one sample was collected 100 cm outside of the drip line. No vegetation was available for sampling. Seven soil samples were collected around tree L-31-3: four below the drip line, one from the original soil pit with elevated arsenic concentrations at a depth 15 cm below the original sample, and two 50 and 100 cm downgradient from the original soil pit, respectively. One foliage sample of *Arctostaphylos uva-ursi* (bearberry) was collected next to the original soil pit. Deep snow cover prevented vehicular access to site Q-31A; therefore additional samples were not collected.

Soil arsenic concentrations in the second set of eight samples collected around tree J-11-1 were well below regional background levels as well as both CCME and BC MOE criteria (Table 4.2). Concentrations averaged 0.8 ppm, and ranged from 0.6 to 1.3 ppm. Arsenic levels in the second set of seven soil samples collected around L-31-3 averaged 0.9 ppm and ranged from 0.4 to 2.7 ppm. These concentrations were well

below regional background levels and soil quality guidelines (SQGs) for arsenic. Total arsenic in the foliage sample from site L-31 was 0.4 ppm.

These results suggest that the elevated soil arsenic concentrations identified during initial field sampling are probably isolated to small pockets of surface contamination located within 2 m of MSMA-treated trees. The isolated nature of elevated soil arsenic implies point-source contamination rather than transfer of arsenic from treated trees to the surrounding environment. Tree J-11-1 was situated on the side of an active forest service road, while tree L-31-3 was located downslope from the Princeton Highway on a steep gradient with uneven terrain, making the likelihood of MSMA spillage during application plausible.

4.1.3 Estimated Province-Wide Volume of Soil Exceeding Environmental Quality Guidelines

Measured soil arsenic concentrations were used to approximate the total volume of soil in British Columbia with arsenic concentrations exceeding the CCME SQG, in order to estimate the potential impact of MSMA-usage on forest soils (see Appendix C for complete calculations). The CCME SQG for arsenic of 12 ppm was selected, as it represents a more conservative level than those recommended by the BC MOE (Table 4.2). The initial sample results indicate that 5 % of all treated trees sampled have associated soil arsenic concentrations in excess of the CCME SQG. It follows that approximately 5,000 MSMA-treated trees in BC could have associated arsenic concentrations in excess of the CCME SQG.

The estimated volume of soil associated with an individual tree that could have an arsenic concentration of more than 12 ppm was calculated using results from tree L-31-3. The maximum soil arsenic concentration (62 ppm) was associated with this tree, meaning these soil volume calculations represent a worst-case scenario encountered through this sampling program. Calculations indicate that about 0.1 m^3 of soil with arsenic in excess of 12 ppm is present around tree L-31-3. Applying this number to the entire province, approximately 450 m^3 of soil could contain arsenic concentrations in

excess of the CCME SQG. This volume corresponds to approximately 56 standard dump truck loads of soil (each load of 8 m^3) or approximately 0.2 % of the total forested area in the province treated with MSMA.

4.1.4 Estimated Soil Arsenic Associated with Decomposition of MSMA-Treated Trees

Research into the distribution of arsenic in MSMA-treated conifers indicates that the majority of arsenic is concentrated between the base of the tree and 2 m height, and in the outer 2 cm of conductive tissue (phloem and outer xylem). The remaining arsenic is translocated into the foliage of the tree (Manville *et al.,* 1988; Maclauchlan *et al.,* 1987; 1988), and enters the soil around the drip line of the tree when needles fall to the ground and decompose.

Although soil arsenic associated with decomposed foliage from MSMA-treated trees was quantified during the sampling program (see previous discussion), conifer wood tissue is resistant to decomposition. Thus, MSMA-treated trees remain standing at present despite the fact that they are no longer alive. If left in place, however, MSMA-treated trees will eventually fall and decompose on the forest floor. For that reason, arsenic concentrations measured in wood cores were used to estimate surface soil (upper 10 cm) arsenic levels that would result from the *in-situ* decomposition of MSMA-treated trees (see Appendix C for detailed calculations). These calculations were purely hypothetical and assumed that: a) all total arsenic contained in wood tissue was released at the same time; b) total arsenic goes directly into the upper 10 cm of surface soil; and c) total arsenic was not diluted by the addition of decomposing wood tissue to the forest soil. In addition, calculations assumed that arsenic in the soil prior to decomposition was equivalent to the average concentration measured at control sites.

The highest arsenic concentration (62 ppm) was measured in wood collected from tree M-51-1 in the Cascades Forest District. This concentration was used to get a worst-case estimate of potential soil arsenic levels associated with *in-situ* tree decomposition. Two scenarios were considered to investigate the influence of soil type on potential arsenic concentrations. Lodgepole pine duff (bulk density 200 kg/m^3; Hirsch

and Pengelly, 1999) was used to represent sites with organic soils and silt loam (bulk density 1200 kg/m^3; Pedosphere, 2009) was used to represent sites with mineral soils. For the silt loam scenario, soil arsenic concentrations were below the SQG of 12 ppm. For the duff scenario, results M-51-1 indicate that a total of 0.1 m^3 of soil could contain arsenic concentrations in excess of the SQG and this volume corresponds to approximately 1.5 wheelbarrow loads (for a medium-sized 6 ft^3 wheelbarrow).

The volume of soil in the entire province of BC potentially containing arsenic above the CCME SQG associated with *in-situ* decomposition was estimated using wood core results for the 60 MSMA-treated trees sampled. For the silt-loam scenario, soil arsenic concentrations were below the SQG. For the duff scenario, results indicate that decomposition could result in soil arsenic above SQG for 38 % (23 out of 60) of MSMA-treated trees sampled, with an average of 0.1 m^3 of soil associated with each of these trees. Applying these results to the entire province of BC, approximately 8,000 m^3 of soil could contain arsenic concentrations in excess of the CCME SQG. This volume corresponds to approximately 1000 standard dump truck loads of soil or to 5 % of the total forested area in the province treated with MSMA.

Table 4.1. Summary of wood core, soil, and foliage arsenic (As) concentrations for Nadina Forest District samples

Category	Wood core As data		Soil As data			Foliage As data		
			Treated		Control	Treated		Control
	Treated	Control	Sampled below drip line	Sampled 1 m outside drip line	Sampled below drip line	Sampled below drip line	Sampled 1 m outside drip line	Sampled below drip line
Average concentration (ppm)	10.2	nd	4.8	4.6	3.3	0.2	nd	nd
Minimum concentration (ppm)	nd	nd	2.2	1.8	1.2	nd	nd	nd
Maximum concentration (ppm)	55	0.5	10	9.8	7.1	0.9	nd	nd
Total number of samples	30	20	30	30	20	33	33	22
95 UCL (ppm)	26	0.2	5.8	5.3	4.0	0.3	n/a	n/a
Number of samples exceeding SQGs	n/a	n/a	0	0	0	n/a	n/a	n/a

nd = arsenic concentration below analytical detection limits (0.2 ppm)
n/a = not applicable
SQG = soil quality guidelines
95 UCL = 95 % upper confidence limit, meaning that arsenic concentrations in 95 % of samples collected are below the listed values.

Table 4.2. Federal (CCME) and provincial (BC) surface soil quality guidelines (SQGs) and background concentrations for arsenic (As).

Land-use Designation	Agricultural	Residential	Commercial	Industrial
	(ppm)			
As SQGs (CCME[1]/ BC[2])	12 / 20	12 / 30	12 / 50	12 / 50
Nadina background As[3]	15			
Cascades background As[3]	25			

[1]CCME 2001
[2]BC MOE 1995
[3]BC MOE 2005

Table 4.3. Summary of wood core, soil, and foliage arsenic (As) concentrations for Cascades Forest District samples. The number of samples exceeding SQGs are highlighted in red.

Category	Wood core As data		Soil As data			Foliage As data		
			Treated		Control	Treated		Control
	Treated	Control	Sampled below drip line	Sampled 1 m outside drip line	Sampled below drip line	Sampled below drip line	Sampled 1 m outside drip line	Sampled below drip line
Average concentration (ppm)	14	0.2	4.8	2.6	2.6	0.3	nd	nd
Minimum concentration (ppm)	nd	nd	0.4	0.7	nd	nd	nd	nd
Maximum concentration (ppm)	62	1.5	62	5.4	6.8	0.7	nd	nd
Total number of samples	30	20	45	30	20	8	6	5
95 UCL (ppm)	21	nd	20	2.9	3.2	nd	nd	nd
Number of samples exceeding SQGs	n/a	n/a	**3**	0	0	n/a	n/a	n/a

nd = arsenic concentration below analytical detection limits (0.2 ppm)
n/a = not applicable
SQG = soil quality guidelines
95 UCL = 95 % upper confidence limit, meaning that arsenic concentrations in 95 % of samples collected are below the listed values.

5.0 Risk Assessment

This risk assessment includes estimates of risk to human health for exposure to arsenic from the organoarsenic herbicide MSMA sold in Canada under the product name Glowon®. Concerns about the health of humans who may be in contact with the trees that have been treated with this product have been raised. This assessment considers possible exposure scenarios (both realistic and conservative) for human contact with media that have been contaminated with MSMA. Arsenic is the only compound which has been included in this risk assessment. Risk assessment is only valuable in areas of potential concern where concentrations of contaminants exceed guideline criteria and background concentrations. Risk assessment is not applied to concentrations of contaminants which are below these values.

5.1 Environmental Behaviour of MSMA

5.1.1 Fate of MSMA in the Environment

The body of knowledge about the fate of MSMA in the environment results from its use in two scenarios: as a weed killer, most commonly for cotton crops, and as a control for conifer beetles, such as the application discussed in this report.

As a weed killer MSMA is sprayed on crops and literature is available on crop uptake of the compound via foliar application and absorption, and also through the roots in soil, since the potential exists for soil contamination directly through spraying. Arsenic concentrations in crops are generally affected very little when MSMA is applied both through spraying and in the soil (Zandstra and De Kryger, 2007; Anderson *et al.*, 1978) even when the application rate is more than 100 times (*i.e.* 269 kg/ha) the rate normally used (Baker *et al.*, 1976).

Speciation analysis to determine arsenic compounds in plants after MSMA or MMAA application has been carried out only in two recent studies. In one study MMAA predominated in fruits and stems+leaves of pepper plants when soil was amended with MMAA but the fate of the applied MMAA in the soil was inconclusive (Szakova *et al.*, 2007). In the other study, foliar application of MSMA to peanuts resulted in MMAA in the leaves, which decreased in concentration within days of its application, independently of

irrigation, and MMAA, constituting most, but not always all of the arsenic, was found in kernels (Armbrust and Bridges, 2002). In carrots thought to have been affected by agricultural MSMA use, MMAA predominated, and the presence of a reduced form, methylarsonous acid, MMA(III), as well as thiol (sulphur-containing) derivatives of MMAA were also present (Yathavakilla *et al*., 2008).

Some plants and tree species are known hyperaccumulators of arsenic. Specifically the Chinese brake fern (*Pteris vittata*) is commonly reported on in literature to be a good arsenic hyperaccumulator from soil (Kachenko *et al.,* 2007; Wang *et al.,* 2006; Ma *et al.,* 2001). Douglas fir (*Pseudotsuga menziesii*) trees growing in British Columbia are able to accumulate high concentrations of naturally occurring arsenic (Haug *et al.,* 2004; Warren *et al.,* 1964).

Manville et al. (1988) investigated arsenic speciation in the wood of Douglas-fir (Pseudotsuga menziesii) treated with MSMA to control Douglas-fir beetle and found that the majority of arsenic in wood tissue was as MSMA, with secondary amounts as inorganic arsenic (likely from impurities in the commercial production of MSMA). Another methylated form of arsenic (dimethylarsinic acid, or DMAA) was also detected in wood tissue, suggesting that in-situ biomethylation of MSMA was taking place in the tree subsequent to application. As previously mentioned (Results and Discussion section) the location of the arsenic in the conifers treated in the present study is likely the foliage, since translocation of MSMA is commonly observed (*e.g.* Manville et al., 1988; Maclauchlan *et al.*, 1987; 1988, Szakova *et al*., 2007), and in the outer 2 cm of conductive tissue (phloem and outer xylem). The speciation of arsenic in foliage is likely predominantly MMAA along with some inorganic arsenic and possibly DMAA, and in the wood it is likely MMAA.

In soils, half lives ranging from 22 to 187 days have been described for MSMA (Woolson *et al.*, 1982; Akkari *et al.*, 1986), with longer half lives associated with drier and colder conditions (Akkari *et al*., 1986). The half life of a contaminant indicates the amount of time required to breakdown the chemical to half of its initial concentration. Losses of total arsenic in field experiments have been attributed to microbial volatilization (*e.g.* 14-15%; Woolson and Isensee, 1981); other estimates obtained by

measuring arsines are lower (<2%; Sierra-Alvarez *et al.*, 2006). MSMA is transformed, most likely via microbial activity, to mostly inorganic As(V) and some DMAA under aerobic conditions (Von Endt *et al.*, 1968; Woolson *et al.*, 1982; Sierra-Alvarez *et al.*, 2006; Chen *et al.*, 2008; Feng *et al.*, 2005), which are the most commonly encountered conditions in surface soils. In anaerobic soils, however, mineralization does not take place, and only the reduction of MSMA to MMA(III) has been observed, in 5-47% yield (Sierra-Alvarez *et al.*, 2006). In forest soils, it is most likely that MSMA in decomposing foliage or wood would be mineralized to As(V) but methylation to DMAA or the formation of minor amounts of volatile arsines cannot be discounted.

When MSMA is applied at the rates recommended for weed control, soil arsenic concentrations appear to not accumulate to phytotoxic concentrations (Woolson and Isensee, 1981; Robinson, 1975), but when higher application rates (greater than six times the recommended rate) were used, arsenic accumulation in soil (up to 133 ppm) and phytotoxicity to rice were observed (Robinson, 1975). Increases in sediment arsenic concentrations at golf courses that use MSMA have been noted (up to 300 ppm, Pichler *et al.*, 2008). Arsenic is generally retained in the top 10-15 cm with deeper (30 cm) accumulation resulting with mixing or when very high application rates are used (Robinson 1975, Hiltbold et al. 1974, Pichler et al. 2008).

MSMA has a high adsorption affinity for iron oxide minerals similar to that for inorganic As(V) (Jackson and Miller, 2000; Lafferty and Loeppert, 2005; Zhang *et al.*, 2007); for both species, soil derived inorganic colloids and/or dissolved organic matter can increase their leachability (Chen *et al.*, 2006; Chen *et al.*, 2008). In sand, As(V) is adsorbed more strongly, but MMAA's adsorption is enhanced by the presence of clay (Hiltbold *et al.*, 1974; Chen *et al.*, 2008). Thus in most cases, because MSMA is degraded quickly to inorganic As(V), and the adsorption characteristics of the two species are similar in typical (iron oxide-containing) soils, MSMA's behaviour in soil can be approximated by the adsorption and leaching characteristics of inorganic As(V).

Surface waters are not an environmental pathway of concern in the present study. Even when they are, increases in arsenic concentrations were observed in only some surface waters in agricultural areas and golf courses, in locations of high uses of

both MSMA (as well as the disodium salt of MMAA) and DMAA, and only during high application times (Pichler *et al.*, 2008; Bednar *et al.*, 2002). A predominance of inorganic arsenic species in most water samples from the agricultural areas suggests that the MMAA and DMAA degraded quickly or are sorbed to soil components (Bednar *et al.*, 2002).

5.1.2 MSMA Toxicity

Analyzing the toxic effects of arsenic is complex because arsenic can exist in several different chemical forms, both inorganic and organic, all which have varying levels of toxicity. In addition, the toxicity of arsenic is also dependent on the exposure dose, frequency and duration of exposure, age, gender, individual susceptibilities, genetic, and nutritional factors (Tchounwou *et al.*, 1999; 2002; ATSDR 2008). Few clinical observations have been recorded of humans known to have been exposed to MSMA or closely related compounds (Dost, 1995).

In general, research has shown that arsenic exerts its toxic effect through impairment of cellular respiration, the inhibition of various mitochondrial enzymes, and the uncoupling of oxidative phosphorylation (a metabolic pathway; ATSDR 2008). In addition, arsenic can induce oxidative stress and may also be responsible for cellular toxicity or carcinogenicity because of arsenic-generated radical species (Yamanaka and Okada, 1994, Kumagai and Sumi, 2007). Most toxicity results from the ability of arsenic to interact with sulphydryl groups of proteins and enzymes, and to substitute for phosphorous in a variety of biochemical reactions (ATSDR, 2008). Inorganic arsenic is generally considered to be the most toxic form of arsenic and is classified as a human carcinogen (US EPA, 2006).

MSMA is an organoarsenical form of arsenic and is considered to have low to moderate acute toxicity via the oral, dermal, and inhalation routes, meaning it is less toxic than inorganic forms of arsenic. A study by Tchounwou *et al.* (2002) found that inorganic arsenic (arsenic trioxide) was about 20 times more toxic (*i.e.* hazardous) to human liver carcinoma (cancer) cells than MSMA, and that while inorganic arsenic

caused significant damage to DNA, MSMA did not. Following oral exposure to MSMA, the target organs are believed to be the gastrointestinal tract, particularly the large intestine, and kidneys. A review of toxicity studies relevant to MSMA is provided in Dost (1995).

The primary concern for MSMA is not its inherent toxicity, but the potential for it to transform into more toxic forms of arsenic and become mobile in the surrounding environment. This concern formed the basis for the 2006 US Environmental Protection Agency (US EPA) decision not to re-register MSMA for use as an herbicide (US EPA, 2006)[1].

As previously mentioned, DMAA is a possible metabolic product in trees or in soil amended with MSMA. This organoarsenical is the predominant metabolite of arsenic in mammals (Dost, 1995). Although of lower toxicity than inorganic forms of arsenic (approximately 10 times less toxic: Kaise *et al.* 1985; 1989), evidence that DMAA itself has toxic properties does exist. Research has shown that DMAA has the ability to induce lesions in the lungs of both mice and rats and in human lung cells *in vitro*. DMAA may also act to promote urinary bladder, kidney, liver and thyroid gland cancers in rats. Collectively, these data suggest that DMAA is a carcinogenic substance (Kenyon and Hughes, 2001).

5.2 Potential Exposure to Arsenic

Humans may be exposed to arsenic (as MSMA) applied to lodgepole pine in BC through the following media:

[1] For the purpose of this risk assessment it was assumed that all of the arsenic was in the more toxic inorganic form.

5.2.1 Surface soil

Humans may potentially come in contact with arsenic in soil through incidental ingestion (normal hand to mouth activities), inhalation of soil particles, or through dermal contact with contaminated soils. However, inadvertent ingestion of soil is typically the most significant exposure pathway to contaminants such as arsenic (Basta *et al.*, 2002). Although 95 % of soil samples collected around MSMA-treated trees in the Nadina and Cascades Forest Districts were below both background (*e.g.* naturally occurring) and guideline soil arsenic levels, three soil samples from the Cascades Forest District exceeded the guideline set by the CCME. The maximum measured concentration of arsenic in soil (62 ppm in sample L-31-3-D) was used in the risk assessment as it provides the worst-case estimate of the health risks posed by concentrations of arsenic in soil as a result of MSMA applications to trees.

5.2.2 Wood

Arsenic in the wood of MSMA-treated trees was considered in this risk assessment because concentrations in wood cores collected from MSMA treated trees were elevated compared to concentrations in non-treated trees. Although the likelihood of humans coming in contact with the arsenic in the wood is limited, certain situations that may increase the likelihood of contact (*e.g.* forestry worker) have been included in this risk assessment. The maximum concentration of arsenic in the wood cores was detected in the Cascades Forest District (62 ppm in tree M-51-1) and was used in this risk assessment.

The Ministry of Forests and Range MSMA policy has been put in place to minimize the potential for exposure to MSMA treated wood (BC MFR 2007a). The policy states that all MSMA treated trees encountered shall not be milled, harvested, removed or burned thus minimizing the potential exposure routes such as inhalation of sawdust or smoke. Therefore, only accidental dermal contact of a forestry worker with MSMA treated wood which is underneath the bark has been considered in this risk assessment. It is unlikely that arsenic would be removed by dermal contact from the

bark of trees because the majority of arsenic is contained within the phloem and outer xylem of the tree as outlined in the Results and Discussion section.

5.2.3 Harvested foodstuffs

Humans may potentially come in contact with arsenic by harvesting and consuming foodstuffs growing around MSMA-treated trees because berries, mushrooms and other edible plants may take up arsenic from the soil (Wang and Mulligan, 2006).

The uptake of arsenic into edible foods and plants will be altered by the soil concentrations, plant species and the form of arsenic (Wang and Mulligan, 2006). In this study attempts were made to collect edible foods from MSMA treated tree stand areas but none could be found. However, consideration was given to the potential for exposure through this media. As a surrogate, the maximum foliage arsenic concentration determined in MSMA treated stand areas was used as the potential arsenic concentration contained in edible foods growing in these areas. Literature on arsenic in foods was reviewed to provide a basis for this practice. Although concentrations of arsenic in foodstuffs collected from soils impacted by MSMA-treated trees have not been reported in the literature, they have been reported for other arsenic-contaminated sites. For example, concentrations of inorganic arsenic in mushrooms collected from mining-impacted soils in Yellowknife, NT, Canada averaged 3.4 ppm (n=7) fresh weight. Concentrations in berries averaged 0.5 ppm (n=27), while foliar arsenic concentrations averaged 1.8 ppm (n=11), and soil concentrations averaged about 790 ppm (n=18). These results indicate that the uptake of arsenic into foliage is generally greater than the uptake of arsenic into food items such as berries, and is roughly equivalent to the uptake of arsenic into mushrooms for samples collected on soils with similar arsenic concentrations (Reimer *et al*., 2001).

In this study, the uptake of arsenic from the soil into plants collected from the Cascades and Nadina Forest Districts was low (average of 0.3 ppm). As well, detectable concentrations of arsenic in the foliage samples was extremely localized

around the MSMA treated trees which was supported by the fact that all samples taken at 1m outside of the drip line in both districts did not contain detectable arsenic concentrations. The maximum concentration of arsenic in plants (0.9 ppm from sample 7603-2-D) was measured within the drip line of a treated tree in the Nadina Forest District.

Based on this information risk estimates in this study have been calculated with and without the consumption of harvested foods growing around MSMA-treated trees. A discussion of the impact of harvested food consumption follows the risk calculations. Where harvested food consumption was included, the maximum arsenic concentration measured in foliage from the Nadina Forest District was used as an estimate of the concentration of arsenic in edible foods growing under the drip line of MSMA-treated trees.

5.3 Exposure Scenarios Examined

A number of scenarios were considered in which a human could potentially come into contact with the arsenic associated with MSMA application in BC. They represent both practical situations (*e.g.* forestry workers, hikers) and hypothetical scenarios (*e.g.* maximum exposures based on year-round visiting). Since all of the scenarios represent maximum or worst-case exposure, they will also encompass individuals who have less than the modelled exposure (*e.g.* forestry workers or hikers who are actually spending less than the modelled time at MSMA-treated sites). This risk assessment does not investigate health threats associated with MSMA that are posed by forest fires because there are too many unknown variables to develop an accurate model. In addition, it is likely that other health threats associated with fire alone (*e.g.* inhalation of smoke and physical threats) would outweigh the threat posed by combustion of MSMA-treated trees. Contact with water of any kind (surface or ground) is also not included in this risk assessment. The BC Forest and Range Practices Act and the Integrated Pest Management Act attempts to minimize pesticide impacts to water bodies through the

standard requirement of a 10-m pesticide-free zone adjacent to a water body (BC MFR, 2003; BC MOE 2005).

Toddlers have been included for most situations because they are considered the most sensitive receptors to contaminants in the environment. The toddler was not included in the forestry worker scenario, as this is not realistic. Toddlers are not assessed for cancer risk as this is covered under adult exposure.

The characteristics of each of the receptors included in the risk assessments can be seen in Table 5.1.

Table 5.1. Characteristics of receptors used in the risk assessment. Toddler and adult receptor information taken from (HC, 2008) and manual labourer information was taken from the construction worker scenario in (HC, 2004b).

Receptor	Toddler	Adult	Manual Labourer
Age	7 mo. - 4 y	≥ 20 y	≥20 y
Body weight (kg)	16.5	70.7	70.7
Soil ingestion rate (g/d)	0.08	0.02	0.1
Inhalation rate (m^3/d)	9.3	15.8	15.8
Water ingestion rate (L/d)	0.6	1.5	1.5
Skin surface area (cm^2)			
- hands	430	890	890
- arms	890	2,500	2,500
- legs	1,690	5,720	5,720
- total	6,130	17,640	17,640
Soil loading to exposed skin (g/cm^2/event)			
- hands	1.00E-04	1.00E-04	1.00E-03
- surfaces other than hands	1.00E-05	1.00E-05	1.00E-04
Food ingestion (g/d)			
- root vegetables	105	188	188
- other vegetables	67	137	137
- fish	56	111	111

5.3.1 Practical Scenarios:

Hiker

This scenario was designed to include the most probable exposures of the general public to MSMA-treated trees and considers an adult or toddler hiker visiting forested areas containing MSMA-treated trees five times per year and spending six hours per day in the treated area. This group may come in contact with soil through dermal contact, inhalation of soil particles and indirect ingestion (*e.g.* soil on hands is transferred to food). There is also the potential that the hiker may ingest berries or other foodstuffs that grow in the contaminated areas. The exposure factors included in the risk estimate for a hiker can be seen in Table 5.2.

Table 5.2. Exposures included for the exposure scenario for the hiker receptor.

Exposure factor	Receptor	Adult	Toddler
Time spent on site	(d / yr)	5	5
	(hrs / d)	6	6
	(yrs)	60	4.5
Soil Contact	Ingestion	✓	✓
	Dermal	✓	✓
	Inhalation of particles	✓	✓
	Inhalation of vapours	x	x
Wood Contact	Dermal	x	x

✓ Included in exposure pathway

x Not included in exposure pathway

Hiker in a decomposing forest

This scenario considers human contact to arsenic from MSMA-treated trees falling to the ground, decomposing and distributing the wood-bound arsenic into the surrounding soil. Calculations suggest that this scenario would produce a maximum surface soil arsenic concentration of 60 ppm (see Results and Discussion, and

Appendix C), which is below the maximum measured soil concentration of 62 ppm (sample L-31-3-D). Risk calculations were not completed for this scenario since the maximum measured soil concentration was used in the hiker scenario (see above), which provides a more conservative estimate of risk from MSMA-derived arsenic in soil than the hiker in a decomposing forest scenario.

Forestry worker

Information regarding forestry worker activity and site use was provided by BC MFR staff (Burleigh, 2009). This scenario estimates that a forestry worker involved in block layout, timber cruising, etc. spends eight-hour days, five days per week, 26 weeks per year in the field (based on 60 % field work and 40 % office work). It is estimated that 0.3 % of all forest blocks in BC contain MSMA-treated trees (Burleigh, 2009); however, to be conservative this risk assessment assumed that 10 % of the time stated above is actually spent working with the MSMA treated trees.

Exposure factors for the forestry worker reflect increased exposure to soil and dust associated with manual labour. Risk estimates have been calculated both including and excluding dermal contact with MSMA-treated wood as the likelihood of dermal contact with wood is low. Although dermal absorption factors for arsenic in soil have been characterized, this is not true for arsenic in MSMA-treated wood. Because of the lack of applicable estimates, when dermal contact was included in risk calculations, absorption of arsenic in MSMA-treated wood was assumed to be 100 %.

However, we believe that the use of 100% dermal bioavailability (see 5.4.2) from wood is unrealistically conservative. Similar to the behaviour of arsenic in soil, it is expected that arsenic in treated wood will become bound to elements within the tree and therefore not be 100 % available for absorption. Hand-loading studies of arsenic from chromated copper arsenate (CCA)-treated wood indicated a range of 0.005 $\mu g/cm^2$ to 0.53 $\mu g/cm^2$ of surface loading for toddler and adult hands (MEDHS, 1998; SCS, 1998). Although the application and chemistry of CCA (a wood preservative) differs from MSMA, this provides evidence that dermal exposure to arsenic from handling treated

wood is minor. For this reason and those which pertain to BC MFR policies which minimize dermal contact with wood risk estimates that excluded dermal contact are thought to be the more accurate and appropriate calculation.

Forestry worker characteristics are reflected in the manual labourer column in Table 5.1 and the exposure factors considered in the risk estimates are located in Table 5.3.

Table 5.3. Exposures included for the exposure scenario for the forestry worker receptor.

Exposure factor	Receptor	Adult
Time spent on site	(d / yr)	13
	(hrs / d)	8
	(yrs)	40
Soil Contact	Ingestion	✓
	Dermal	✓
	Inhalation of particles	✓
	Inhalation of vapours	x
Wood Contact	Dermal (practical exposure)	x
Wood Contact	Dermal (unlikely exposure)	✓

✓ Included in exposure pathway

x Not included in exposure pathway

5.3.2 Worst Case Scenario:

Maximum exposure

The maximum exposure scenario represents the unlikely event of someone spending his or her entire life on an MSMA-treated site, which could potentially happen if the land were clear-cut and a housing development erected on site (Table 5.4). This worst-case scenario does not consider the likelihood that construction on MSMA-impacted sites would render soils with elevated arsenic concentrations either inaccessible (*e.g.* covered by buildings and roadways) or mixed with clean soil (thus reducing arsenic concentrations).

Table 5.4. Exposures included for the maximum exposure scenario.

Exposure factor	Receptor	Adult	Toddler
Time spent on site	(d / yr)	365	365
	(hrs / d)	24	24
	(yrs)	60	4.5
Soil Contact	Ingestion	✓	✓
	Dermal	✓	✓
	Inhalation of particles	✓	✓
	Inhalation of vapours	x	x
Wood Contact	Dermal	x	x

✓Included in exposure pathway

x Not included in exposure pathway

5.4 Risk Calculations

The risk posed to receptors in each of the scenarios outlined in Section D has been calculated following Health Canada guidance (HC, 2004). The calculated risk takes into account the estimated daily intake (EDI) of arsenic for the various scenarios considered, and compares that value with a benchmark dose that is known to cause adverse human health effects. If the daily dose exceeds the benchmark dose, the concentrations of arsenic in the environment are assumed to have the potential to induce adverse health effects. The benchmark dose of a contaminant is referred to as the toxicity reference value (TRV).

5.4.1 Selection of Toxicity Reference Values

Arsenic is known to induce both carcinogenic and non-carcinogenic endpoints in humans and both have been considered in this human health risk assessment. TRVs for arsenic are available for the ingestion and inhalation exposure pathways. Both chronic and acute oral ingestion TRVs have been developed for arsenic. Chronic exposure (greater than 90 days) is applicable for the maximum exposure scenario (Health Canada, 2007). The acute oral ingestion TRV has been used as the benchmark

dose for the hiker and forestry worker where exposure is limited to less than 14 days per year. Acute cancer slope factors are not available for either exposure route. The TRVs used in this risk assessment are presented in Table 5.5.

Table 5.5. Toxicity reference values for arsenic used in this risk assessment.

Chemical of Potential Concern	Route of Exposure	Non-Carcinogenic	Carcinogenic
		TRV value (Tolerable Daily Intake) (mg/kg-d)	TRV value (Cancer Slope Factor) $(mg/kg\text{-}d)^{-1}$
Arsenic	Ingestion	0.0003*	1.8
	Inhalation	n/a	28
	Acute ingestion	0.005[a]	n/a

Source: Health Canada (2008), * Source: US EPA (1998), [a] Source ATSDR (2008).

5.4.2 Bioavailability

The bioavailability of a substance refers to the concentration of a contaminant that reaches systemic circulation (bloodstream) (Oomen *et al.*, 2002), and is represented by the relative absorption factor (RAF) in risk assessment calculations. The bioavailability of all contaminants for the inhalation and ingestion exposure pathways are assumed to be 100 % (a factor of 1.0 applied). Although several studies indicate the reduced bioavailability of arsenic in soil, these studies have only been accepted by regulatory bodies for use in some not all risk assessments (Freeman *et al*., 1995; Ruby *et al*., 1996; Rodriguez *et al*., 1999). Site-specific values of arsenic bioavailability in soils impacted by MSMA-treated trees are not available; however, relative dermal absorption

factors (RAF_{derm}) for contaminants in soil are available from Health Canada (2004). The dermal RAF value for arsenic in soil used in this risk assessment is 0.03.

We were unable to find studies of arsenic bioavailability through dermal contact or ingestion of MSMA-treated wood. The most relevant studies of the bioavailability of arsenic in wood are for CCA-treated wood, which estimated 47 % bioavailability from the ingestion of dislodgeable CCA-treated wood (as sawdust) fed to dogs (Peoples, 1976; Peoples and Parker, 1979). However, since the applicability of these studies to MSMA-treated wood has not been characterized, we assumed 100 % arsenic bioavailability for the dermal, oral and inhalation pathways.

5.4.3 Summary of Exposure Factors Used in Risk Calculations

The characteristics used in the risk calculations for each of the three receptors modelled can be found in Table 5.1. The individual on-site exposure can be found in each of the tables associated with the modelled scenarios and the TRVs used can be found in Table 5.5. Other factors have been tabulated in Table 5.6 for reference.

Table 5.6. Factors used in the risk assessment calculations

Soil concentration (ppm)	Wood concentration (ppm)	Relative absorption factors (Soil)			Relative absorption factors (Wood)
		Ingestion	Inhalation	Dermal	Dermal
62	62	1.0	1.0	0.03	1.0

5.4.4 Risk Characterization – Non-carcinogenic

Risks posed by non-carcinogenic contaminants were calculated by comparing the EDI exposure on site with the appropriate TRVs for arsenic. A target hazard quotient (HQ) of 1.0 (exposure less than or equal to the TRV) is accepted in British Columbia (Health Canada, 2007). If the HQ is less than or equal to 1.0, the intake of the contaminant on site does not exceed the tolerable level of intake and no adverse health effects are expected. Hazard quotients are calculated for threshold contaminants (those deemed to induce non-carcinogenic endpoints).

The HQ was calculated by:

$$\mathbf{HQ} = \frac{\mathbf{EDI}}{\mathbf{TDI}} \qquad \textbf{Equation 1}$$

Where: EDI = estimated daily intake (mg/kg-d)

TDI = tolerable daily intake (mg/kg-d)

The calculated HQ for each scenario and receptor are presented in Table 5.11 and Table 5.12.

Table 5.7. Hazard quotient values for the practical scenario toddler and adult receptors.

Practical Scenario	Receptor	HQ	Exceeds Risk Criteria
		Ingestion/Dermal	
Hiker	Toddler	8.5E-4	No
Hiker	Adult	6.1E-5	No
Forestry Worker	Adult	9.2E-4	No
	Adult*	1.1E-2	No

*Includes exposure from dermal contact with wood beneath the bark, assuming 100 % bioavailability

Table 5.8. Hazard quotient values for the toddler and adult receptors in the worst case scenario.

Hypothetical Scenario	Receptor	HQ	Exceeds Risk Criteria
		Ingestion/Dermal	
Maximum Exposure	Toddler	1.0	No
Maximum Exposure	Adult	7.4E-2	No

5.4.5 Risk Characterization – Carcinogenic

The incremental lifetime cancer risk (ILCR) associated with exposure to carcinogenic contaminants is calculated by multiplying the daily dose of the on-site contaminant by the cancer slope factor specific to each contaminant. A benchmark of 1 in 100,000 is used to screen contaminants that have the potential of causing an unacceptable potential of developing cancer due to exposure. That is, if the ILCR is $<10^{-5}$, the potential of developing cancer as a result of exposure to carcinogenic contaminants is negligible.

The ILCR was calculated by:

$$\mathbf{ILCR = LADD \times CSF} \qquad \mathbf{Equation\ 2}$$

Where: LADD = lifetime average daily dose (mg/kg-d)

CSF = cancer slope factor $(mg/kg\text{-}d)^{-1}$

The ILCRs calculated for each of the MSMA exposure scenarios are presented in Table 5.13 and Table 5.14.

Table 5.9. Incremental lifetime cancer risk values for the practical scenario adult receptors.

Practical Scenario	Receptor	ILCR			Exceeds Risk Criteria
		Ingestion/Dermal	Inhalation	Total	
Hiker	Adult	5.5E-7	1.0E-9	5.5E-7	No
Forestry Worker	Adult	5.5E-6	2.3E-9	5.5E-6	No
	Adult*	1.0E-4	2.3E-9	1.0E-4	Yes

*Includes exposure from dermal contact with wood beneath the bark, assuming 100 % bioavailability

Table 5.10. Incremental lifetime cancer risk values for adult receptors in the worst case scenario.

Hypothetical Scenario	Receptor	ILCR			Exceeds Risk Criteria
		Ingestion/Dermal	Inhalation	Total	
Maximum Exposure	Adult	4.0E-5	3.0E-7	4.0E-5	Yes

5.5 Influence of Harvested Foodstuffs on Risk Estimates

Arsenic concentrations detected in the foliage sampled around MSMA treated trees has been used to estimate the concentration of arsenic in edible foods growing in this area. The foliage samples collected in this study suggest arsenic transfer to plant matter is unlikely (see Section 4.1.1) and, if present, is localized to areas within the dripline of the treated trees. For the ingestion of foods to be a contributer to risk, foods would have to be harvested directly within the dripline of treated trees.

Risk calculations were performed to estimate the potential for risk in the unlikely event a person were to harvest edible foods from within the dripline of treated trees. All of the scenarios presented previously in the report were re-calculated to include the

consumption of harvested foods. These risk estimates included the conservative assumption that all consumed harvested foods were collected within the drip line of MSMA-treated trees (*i.e.* where the maximum arsenic concentration in plant foliage was measured). In addition, the Health Canada value of 67 g/d or 137 g/d consumption of non-root vegetables for toddlers and adults, respectively (HC, 2004) was used as the value for amount of harvested foodstuffs consumed per day spent in the treated areas. These values correspond to one or two cups of fresh mushrooms or cranberries per day, for toddlers and adults, respectively. These assumptions represent the worst-case scenario, and might not be realistic the majority of the time. The calculations indicate that there is the potential for risk if foods were harvested and consumed from within the dripline of treated trees and consumed in the amounts stated (Table 5.11 to 5.14). Foods acceptable for harvesting (*e.g.* berries, mushrooms) may not grow throughout all of British Columbia, and it is improbable that individuals would be able to forage the quantities recommended by Health Canada solely from within 1m of the drip line of MSMA-impacted trees. However, without evidence to suggest realistic values or exposure scenarios the maximum exposure was used to estimate risk. We believe that these values do not represent a realistic estimate of risk for the majority of individuals potentially encountering MSMA-treated stands.

Table 5.11. Hazard quotient values calculated for the practical scenarios provided for the adult and toddler receptors including consumption of contaminated foods from within the dripline of MSMA treated trees.

Practical Scenario	Receptor	HQ	Exceeds Risk Criteria
		Ingestion/Dermal	
Hiker	Toddler	1.1E-2	No
Hiker	Adult	4.8E-3	No
Forestry Worker	Adult	1.3E-2	No
	Adult*	1.9E-2	No

*Includes exposure from dermal contact with wood beneath the bark, assuming 100 % bioavailability

Table 5.12. Hazard quotient values calculated for the maximum exposure scenario provided for the adult and toddler receptors including consumption of contaminated foods from within the dripline of MSMA treated trees.

Hypothetical Scenario	Receptor	HQ	Exceeds Risk Criteria
		Ingestion/Dermal	
Maximum Exposure	Toddler	13	Yes
Maximum Exposure	Adult	5.9	Yes

Table 5.13. Incremental lifetime cancer risk (ILCR) values calculated for the practical exposure scenarios including consumption of contaminated foods from within the dripline of MSMA treated trees.

Practical Scenario	Receptor	ILCR			Exceeds Risk Criteria
		Ingestion/Dermal	Inhalation	Total	
Hiker	Adult	4.4E-5	1.0E-9	4.4E-5	Yes
Forestry Worker	Adult	8.0E-5	2.3E-9	8.0E-5	Yes
	Adult*	1.8E-4	2.3E-9	1.8E-4	Yes

*Includes exposure from dermal contact with wood beneath the bark, assuming 100 % bioavailability

Table 5.14. Incremental lifetime cancer risk values calculated for the hypothetical exposure scenarios including consumption of contaminated foods from within the dripline of MSMA treated trees.

Hypothetical Scenario	Receptor	ILCR			Exceeds Risk Criteria
		Ingestion/Dermal	Inhalation	Total	
Maximum Exposure	Adult	3.2E-3	2.9E-7	3.2E-3	Yes

5.6 Risks associated with exposure pathways

The effect of each exposure pathway on the EDI was investigated to evaluate the relative contribution of each to the risk outcome. Human health risk was calculated with and without the foodstuffs ingestion pathway. Food consumption was included in the risk assessment as a possible exposure pathway, but the calculations have been based on default assumptions and theoretical situations (*i.e.* foraging berries or mushrooms in the quantities used in the assessment from directly within the dripline of treated trees.) In all scenarios, when consumption of contaminated foods were included in the calculations, this pathway contributed to almost 100 % of the EDI (*i.e.* risk posed; Figure 5-1). This assesment has shown that ingestion of contaminated foods collected within the dripline of treated trees may pose a health risk, but other indicators in this assessment suggest that this pathway is of minimal concern. When consumption of foods is not included, the soil ingestion pathway was the greatest contributor to the EDI, and hence risk (Figure 5-2 and Figure 5-3). We believe that these values represent a more realistic estimate of risk for the majority of individuals potentially encountering MSMA-treated stands.

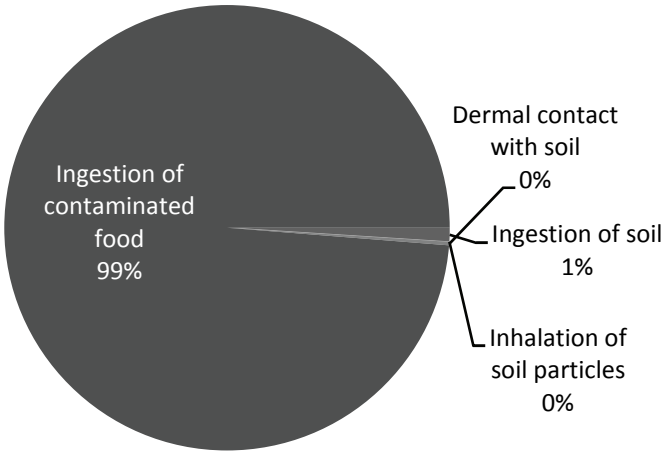


Figure 5-1. Contribution of each exposure pathway to the overall estimated daily intake of arsenic for the adult hiker scenario with harvested food intake.

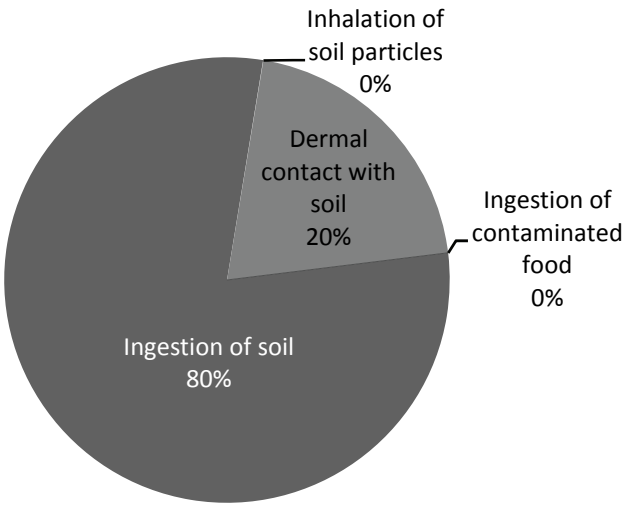


Figure 5-2. Contribution of each exposure pathway to the overall estimated daily intake of arsenic for the adult hiker scenario who is not harvesting food in the contaminated area.

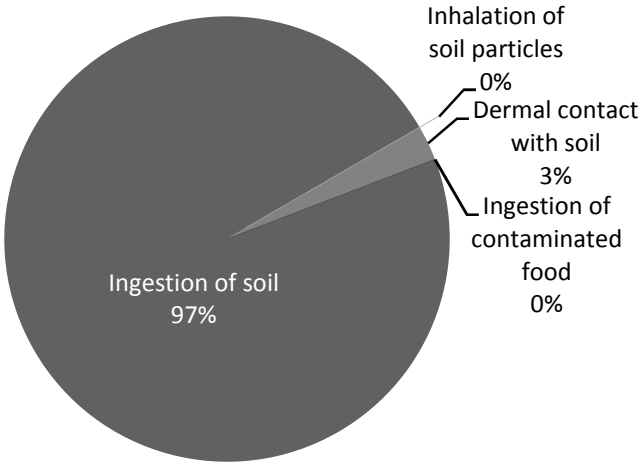


Figure 5-3. Contribution of each exposure pathway to the overall estimated daily intake of arsenic for the worst-case exposure scenario for a toddler who is not consuming food in the contaminated area.

5.7 Assumptions and Uncertainties in the Risk Assessment

Uncertainty is inherent in any risk estimation and conservative assumptions help to account for these uncertainties. This risk assessment also looked at maximum exposure scenarios that are possible, but unlikely to occur.

The key **assumptions** made in this risk assessment are:

- All arsenic measured in wood cores, foliage and soil is inorganic. Inorganic arsenic is the most toxic species to humans and therefore provides a conservative estimate of the risk posed.

- TRVs provided by Health Canada, the US Environmental Protection Agency, and the US Agency for Toxic Substances and Disease Registry accurately reflect doses of arsenic that produce adverse health effects.

- For the scenario in which MSMA-treated trees fall to the forest floor and decompose, we assumed that none of the arsenic would be lost through volatilization from microbial processes, that decomposing wood does not add additional mass to the soil, and that all of the decomposing material stays in place.

- Dermal contact with treated wood was not considered as an operable exposure pathway for the general public (*i.e.* the hiker or maximum-exposure scenario). Arsenic in MSMA-treated trees is concentrated under the bark in the phloem and outer xylem (Maclauchlan *et al.,* 1987, 1988; Manville *et al.,* 1988). Since the general public will not be in contact with this part of the tree, dermal contact was only considered as a possible pathway for forestry workers who have an increased chance compared to the general public of handling treated trees. Exposure scenarios related to the harvesting and milling of treated trees were not considered in this risk assessment, because Ministry of Forests and Range policy states that MSMA-treated trees are not to be harvested or milled (BC

MFR, 2007a). In addition, practices have been put in place to track MSMA-treated trees and ensure they remain in place (BC MFR, 2007a).

- Arsenic concentrations in foliage collected within the drip line of treated trees could be used to estimate arsenic concentrations in harvested foods.

- Volatilization of arsenic from contaminated soil is negligible. This assumption is supported by research indicating that, in general, wood rotting fungi are not gas producers and volatilization of arsenic in soil is at the most a few percent (Reimer *et al.* in press).

The key **sources of uncertainty** associated with the risk estimation for human health are:

- Although the assumptions included in this risk assessment were made with the best available information, it is possible that future or current exposures have not been documented or projected accurately. We used available data to create the most conservative exposure scenarios for plausible uses of sites with MSMA-treated trees. We believe these exposure scenarios provide the best possible estimation of risk given the information available.

- TRVs are based on the best available data from humans and/or animal studies.

- Extrapolation of data from animals to humans can create a measure of uncertainty in the resultant value. Sources of uncertainty associated with interspecies extrapolation come from the choice of animal species that will best represent exposure to humans and the decision of what non-carcinogenic critical endpoint to use in the animal studies. In addition, extrapolation from high-dose exposures, which are often used in human epidemiological toxicity studies, to low-dose exposures can add to the uncertainty in the measurement. To account

for this, a number of uncertainty factors are incorporated into the final TRV value that often gives a much lower representative value than that which is actually expected to induce the endpoint studied.

- The non-carcinogenic inhalation route was not considered in this assessment because TRVs for this route of exposure are not available for arsenic. EDIs were calculated via the inhalation route; however, the values were orders of magnitude lower than the dermal or oral route and this exposure route was deemed negligible.

- Dermal exposure was summed with the exposure from ingestion and compared with the ingestion TRV in accordance with Health Canada guidance (2007) because TRVs were not available for arsenic by the dermal route, and this provides a more conservative estimate of risk. The oral and dermal lifetime average daily doses were summed from the oral and dermal routes and compared with the oral cancer slope factor (CSF) for arsenic because CSFs for arsenic were not available for the dermal route.

6.0 Conclusions

The aim of this study was to quantify total arsenic concentrations in wood, vegetation and soil samples collected from sites containing trees treated with MSMA to control mountain pine beetle populations and to assess risk to human health posed by MSMA-treated trees. For comparison, samples were also collected from similar reference sites that had not been treated with MSMA. The major findings of this study are as follows:

- Arsenic was apparent in most wood cores collected from MSMA-treated trees in both the Nadina and Cascades Forest Districts.
- Although arsenic was detected in most wood cores collected from MSMA-treated trees, levels in 95 % of adjacent soil samples were below both background (*i.e.* naturally occurring) and acceptable soil arsenic levels specified by CCME and the BC MOE.
- Arsenic concentrations in foliage samples collected near treated trees were below or close to the analytical detection limit (0.2 ppm).
- Total soil arsenic exceeded guidelines in three samples (5% of all samples taken) in the Cascades Forest District. Additional delineation sampling around these trees indicated that elevated arsenic levels were isolated to small areas, suggesting point-source contamination (such as MSMA spillage during application).
- The results suggest that arsenic associated with MSMA application is largely confined to the trees that were treated and is not migrating into surrounding soil and vegetation.
- By extrapolating soil arsenic results to all MSMA-treated trees in the province of BC, we estimate that 450 m^3 of surface soil, covering approximately 0.2 % of the total forested area in the province treated with MSMA, could contain arsenic levels in excess of the CCME SQG of 12 ppm.

- Models simulating the hypothetical amount of arsenic released into the soil from MSMA-treated trees falling to the forest floor and decomposing *in-situ* showed that decomposition could possibly lead to elevated soil arsenic in areas with organic-rich surface soils, but not at sites dominated by mineral soil.

- Risks to adult and toddler receptors were calculated for practical and worst-case exposure to MSMA-treated wood, impacted soils, and harvestable foodstuffs in British Columbia forests.

- Arsenic concentrations detected in soil and wood impacted by MSMA treatments do not pose a risk to the general public with infrequent exposure to MSMA treated tree stand areas (*e.g.* a hiker).

- Arsenic concentrations detected in soil and wood impacted by MSMA treatments do not pose a risk to forestry workers working amongst MSMA treated stands who are not coming in direct contact with the wood beneath the bark of MSMA treated trees.

- Calculations show that risk to human health may occur through the consumption of foodstuffs *(i.e.* berries and mushrooms) harvested directly below the dripline of MSMA-treated trees (Figure 6.1 and 6.2)

- We recommend that individuals avoid collecting edible plants within 2 m of MSMA-treated trees.

- Risk to human health may also occur through the handling of wood underneath the bark of MSMA-treated trees (Figure 6.2) and the BC Ministry of Forests and Range MSMA current policy prohibits the harvesting, removal, milling, and/or burning of MSMA-treated trees (BC MFR 2007a) which minimizes exposure to MSMA treated wood.

- We conclude that humans are not at risk in the forests of British Columbia as a result of the use of monosodium methanearsonate MSMA (in attempts) to control infestations of mountain pine beetle.

- This assessment is based on the arsenic concentrations measured in 382 samples collected from the Nadina and Cascades Forest Districts in 2008 and 2009. We believe the conclusion would not be changed by the acquisition of more analytical data.

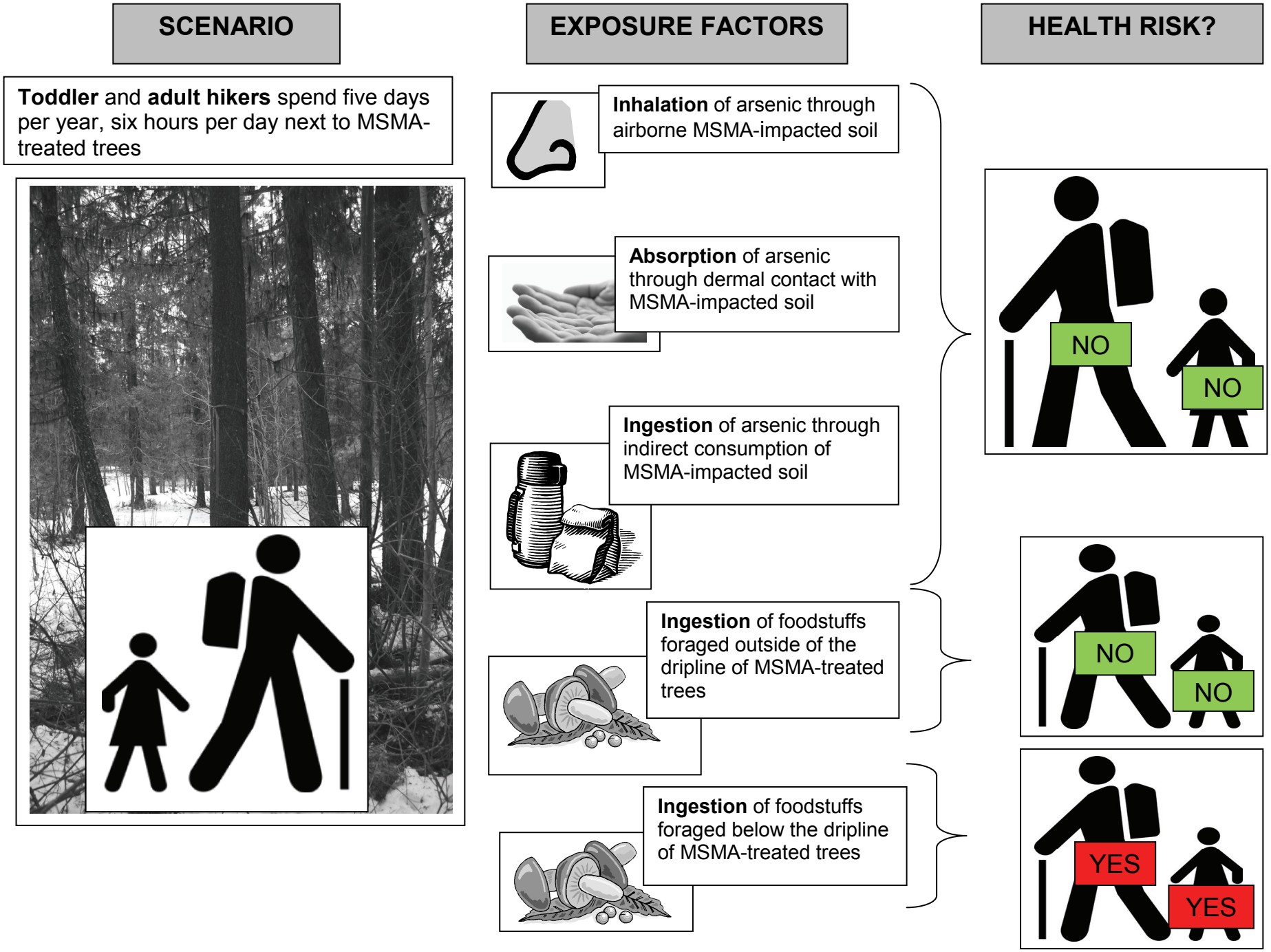


Figure 6-1: Estimated risks to adult and toddler hikers from exposure to MSMA treated tree sites

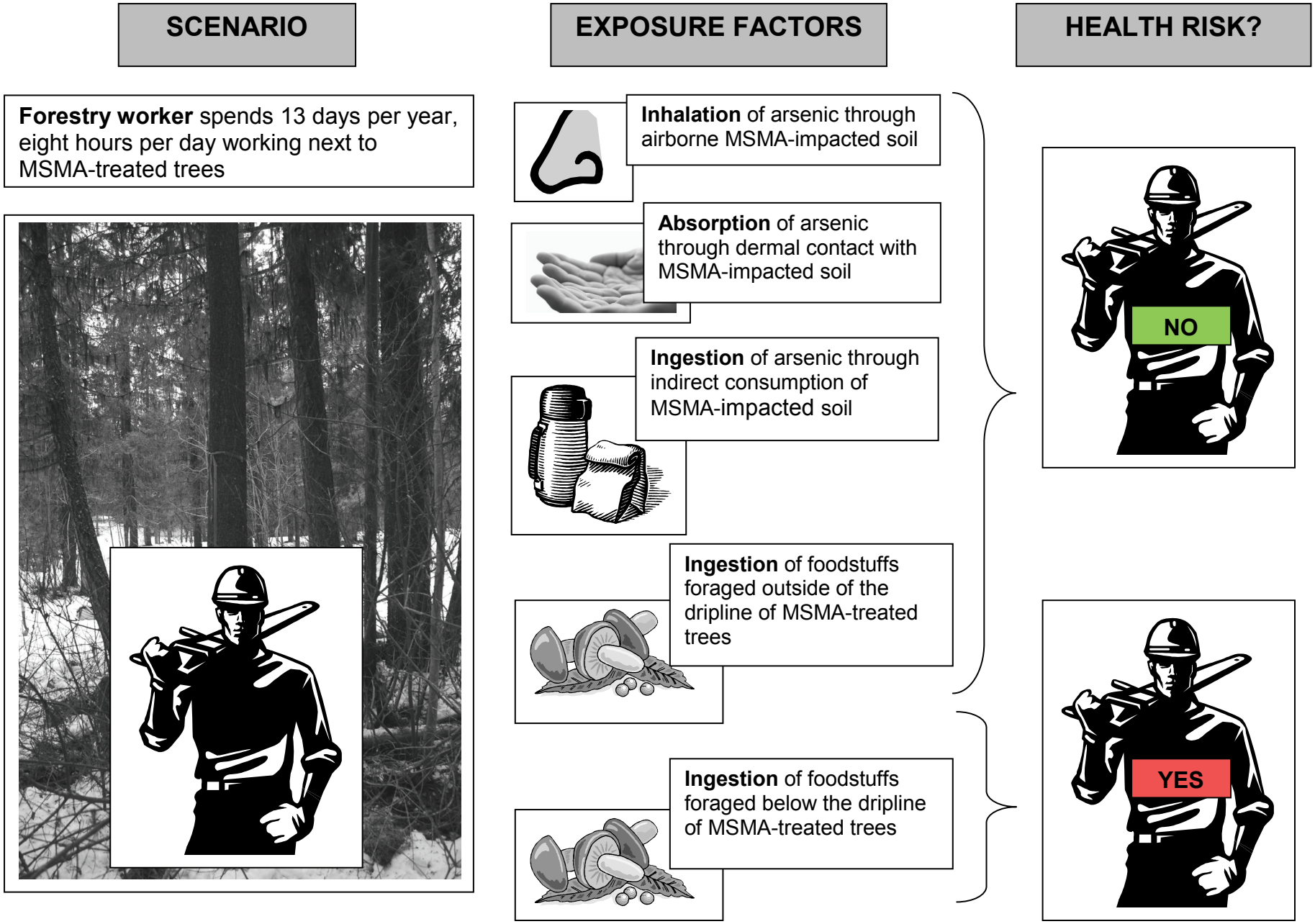


Figure 6-2: Estimated risks to the forestry worker from exposure to MSMA treated tree sites.
***Impropable dermal contact with wood beneath the bark of treated trees may result in increased risk.**

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8.0 Appendices

Appendix A. Quality Assurance/Quality Control

Appendix B. Sample Results

Appendix C. General Calculations

Appendix D. Human Health Risk Assessment Calculations

Appendix A: Quality Assurance/ Quality Control (QA/QC)

This section describes the QA/QC results for the 2008 total arsenic in wood, soil, and plant tissue sampling program performed by the Analytical Services Unit (ASU) of Queen's University, Kingston, ON, for the British Columbia Ministry of Forests and Range. The QA/QC program was implemented to monitor data quality.

Accuracy

ASU monitored accuracy internally with the analysis of standard reference materials (SRMs). For soil samples, the SRMs analyzed were SS-2 from SCP Science (nine samples; Table A-1), and NRC Canada Marine Reference Sediment MESS-3 (10 samples; Table A-2). All samples were within acceptable control limits, with the exception of samples MESS-3-1 and MESS-3-6. Although arsenic concentrations in these samples were outside the ASU control limits, they were within an acceptable range of the standard reference concentration for MESS-3 (21.2 ppm As). For wood core and foliage samples, the SRMs analyzed were: bush branches and leaves (13 samples; Table A-3) and spinach (six samples; Table A-4). All samples were within acceptable control limits. A total of 37 blank samples were also run with the soil, wood core and foliage batches, and results are presented in Table A-5. All element readings from the blanks were below laboratory detection limits.

Precision/Repeatability

ASU monitored analytical precision internally through the use of sample replicates. Average relative standard deviations (RSDs), or coefficients of variation (standard deviation divided by the mean), for sample replicates were expressed as percentages and used to evaluate laboratory precision. Acceptable limits were considered to be less than 40 % RSD. Twenty-six soil samples were analyzed in duplicate and six in triplicate for total arsenic (Table A-6). The RSDs for soil replicates were below 25 %, indicating good precision. A total of 15 and 14 sample duplicates were analyzed during wood core and foliage analysis, respectively (Tables A-7 and A-8). Sample RSDs were below 30 % for wood core and 20 % for foliage duplicates, indicating acceptable precision.

Table A-1: Summary of Arsenic Results for the Internal Soil Standard SS-2

Sample	SS-2 ASU Control Limits for As (ppm)	ASU Mesured As (ppm)
SS-2-1	79 ± 24.2	88.1
SS-2-2	79 ± 24.2	76.4
SS-2-3	79 ± 24.2	77.6
SS-2-4	79 ± 24.2	74.3
SS-2-5	79 ± 24.2	70.3
SS-2-6	79 ± 24.2	67.2
SS-2-7	79 ± 24.2	85.0
SS-2-8	79 ± 24.2	77.9
SS-2-9	79 ± 24.2	75.7

Table A-2: Summary of Arsenic Results for the Internal Soil Standard MESS-3

Sample	MESS-3 ASU Control Limits for As (ppm)	ASU Mesured As (ppm)
MESS-3-1	15.6 ± 2.6	19.0
MESS-3-2	15.6 ± 2.6	16.7
MESS-3-3	15.6 ± 2.6	17.3
MESS-3-4	15.6 ± 2.6	14.9
MESS-3-5	15.6 ± 2.6	17.2
MESS-3-6	15.6 ± 2.6	19.2
MESS-3-7	15.6 ± 2.6	18.1
MESS-3-8	15.6 ± 2.6	16.9
MESS-3-9	15.6 ± 2.6	17.0
MESS-3-10	15.6 ± 2.6	17.2

Table A-3: Summary of Arsenic Results for the Internal Vegetation Standard Bush, Branches, and Leaves (BB&L)

Sample	BB&L ASU Control Limits for As (ppm)	ASU Mesured As (ppm)
BB&L-1	1.16 ± 0.66	1.3
BB&L-2	1.16 ± 0.66	1.2
BB&L-3	1.16 ± 0.66	1.2
BB&L-4	1.16 ± 0.66	1.2
BB&L-5	1.16 ± 0.66	1.2
BB&L-6	1.16 ± 0.66	1.1
BB&L-7	1.16 ± 0.66	1.1
BB&L-8	1.16 ± 0.66	1.1
BB&L-9	1.16 ± 0.66	1.1
BB&L-10	1.16 ± 0.66	1.2
BB&L-11	1.16 ± 0.66	1.2
BB&L-12	1.16 ± 0.66	1.2
BB&L-13	1.16 ± 0.66	1.2

Table A-4: Summary of Arsenic Results for the Internal Vegetation Standard Spinach

Sample	Spinach ASU Control Limits for As (ppm)	ASU Mesured As (ppm)
Spinach-1	nd	nd
Spinach-2	nd	nd
Spinach-3	nd	nd
Spinach-4	nd	nd
Spinach-5	nd	nd
Spinach-6	nd	nd

Table A-5: Arsenic Results for Analytical Blanks

	As (ppm)
Soil Samples	
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Wood Core Samples	
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Foliage Samples	
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd
Blank	nd

nd = below laboratory detection limits (0.2 ppm)

Table A-6: Total Arsenic Results for Analytical Replicates of Soil Samples

Sample	As (ppm)
08-91003	2.3
08-91003	1.9
Average	2.1
Std Dev	0.2
RSD (%)	**11**

Sample	As (ppm)
08-91254	2.4
08-91254	2.1
Average	2.2
Std Dev	0.2
RSD (%)	**9**

Sample	As (ppm)
08-91259	nd
08-91259	nd
Average	n/a
Std Dev	n/a
RSD	**n/a**

Sample	As (ppm)
08-91009	7.2
08-91009	5.8
Average	6.5
Std Dev	1.0
RSD (%)	**15**

08-91047	8.3
08-91047	8.5
Average	8.4
Std Dev	0.1
RSD (%)	**2**

08-91054	4.4
08-91054	4.5
Average	4.5
Std Dev	0.1
RSD (%)	**2**

08-91087	2.8
08-91087	3.6
Average	3.2
Std Dev	0.6
RSD (%)	**18**

08-91119	5.5
08-91119	5.5
Average	5.5
Std Dev	0.0
RSD (%)	**0**

08-91126	4.6
08-91126	4.4
Average	4.5
Std Dev	0.2
RSD (%)	**4**

08-91133	3.0
08-91133	2.5
Average	2.8
Std Dev	0.4
RSD (%)	**13**

08-91165	4.5
08-91165	4.4
Average	4.5
Std Dev	0.1
RSD (%)	**2**

08-91172	6.0
08-91172	5.8
Average	5.9
Std Dev	0.2
RSD (%)	**3**

08-91207	6.0
08-91207	5.7
Average	5.8
Std Dev	0.2
RSD (%)	**3**

08-91220	4.4
08-91220	4.6
Average	4.5
Std Dev	0.1
RSD (%)	**3**

08-91227	2.9
08-91227	4.1
Average	3.5
Std Dev	0.8
RSD (%)	**24**

08-91244	3.8
08-91244	4.5
Average	4.2
Std Dev	0.5
RSD (%)	**12**

08-91251	2.3
08-91251	2.4
Average	2.4
Std Dev	0.1
RSD (%)	**3**

08-91277	2.8
08-91277	2.3
Average	2.5
Std Dev	0.4
RSD (%)	**15**

08-91284	2.4
08-91284	2.3
Average	2.4
Std Dev	0.1
RSD (%)	**3**

08-91291	1.4
08-91291	1.6
Average	1.5
Std Dev	0.1
RSD (%)	**9**

08-91346	1.5
08-91346	1.6
Average	1.6
Std Dev	0.1
RSD (%)	**5**

08-91325	0.9
08-91325	0.9
Average	0.9
Std Dev	0.0
RSD (%)	**0**

08-91332	1.7
08-91332	1.9
Average	1.8
Std Dev	0.1
RSD (%)	**8**

08-91281	23.3
08-91281	26.1
Average	24.7
Std Dev	2.0
RSD (%)	**8**

08-91371	0.5
08-91371	0.7
Average	0.6
Std Dev	0.1
RSD (%)	**24**

08-91378	0.6
08-91378	0.7
Average	0.7
Std Dev	0.1
RSD (%)	**11**

08-91226a	32.9
08-91226a	37.3
08-91226a	28.6
Average	32.9
Std Dev	**4.4**
RSD (%)	13

08-91226b	31.9
08-91226b	28.9
08-91226b	27.0
Average	29.3
Std Dev	**2.5**
RSD (%)	8

08-91281a	23.3
08-91281a	26.1
08-91281a	24.7
Average	24.7
Std Dev	1.4
RSD (%)	**6**

08-91281b	21.2
08-91281b	23.0
08-91281b	20.3
Average	21.5
Std Dev	1.4
RSD (%)	**7**

08-91347a	65.6
08-91347a	67.1
08-91347a	58.1
Average	63.6
Std Dev	4.8
RSD (%)	**8**

08-91347b	68.0
08-91347b	63.7
08-91347b	59.2
Average	63.6
Std Dev	4.4
RSD (%)	**7**

nd = below laboratory detection limits (0.2 ppm)
n/a = calculation not applicable based on nd values

Table A-7: Total Arsenic Results for Analytical Replicates of Wood Core Samples

Sample	As (ppm)
08-91017	1.4
08-91017	2.1
Average	1.8
Std Dev	0.5
RSD (%)	**28**

Sample	As (ppm)
08-91064	12.2
08-91064	10.5
Average	11.4
Std Dev	1.2
RSD (%)	**11**

Sample	As (ppm)
08-91098	nd
08-91098	nd
Average	n/a
Std Dev	n/a
RSD	**n/a**

Sample	As (ppm)
08-91140	nd
08-91140	nd
Average	n/a
Std Dev	n/a
RSD (%)	**n/a**

08-91178	3.1
08-91178	3.7
Average	3.4
Std Dev	0.4
RSD (%)	**12**

08-91185	nd
08-91185	nd
Average	n/a
Std Dev	n/a
RSD	**n/a**

08-91235	32.1
08-91235	29.4
Average	30.8
Std Dev	1.9
RSD (%)	**6**

08-91242	nd
08-91242	nd
Average	n/a
Std Dev	n/a
RSD	**n/a**

08-91270	nd
08-91270	1
Average	n/a
Std Dev	n/a
RSD	**n/a**

08-91301	10.9
08-91301	11.6
Average	11.3
Std Dev	0.5
RSD (%)	**4**

08-91342	nd
08-91342	nd
Average	n/a
Std Dev	n/a
RSD	**n/a**

08-91363	5.6
08-91363	7.4
Average	6.5
Std Dev	1.3
RSD (%)	**20**

08-91356	nd
08-91356	nd
Average	n/a
Std Dev	n/a
RSD	**n/a**

08-91012	15.2
08-91012	26.0
Average	n/a
Std Dev	n/a
RSD	**n/a**

08-91268	nd
08-91268	nd
Average	n/a
Std Dev	n/a
RSD	**n/a**

Table A-8: Total Arsenic Results for Analytical Replicates of Foliage Samples

Sample	As (ppm)
08-91020	nd
08-91020	nd
Average	n/a
Std Dev	n/a
RSD (%)	**n/a**

Sample	As (ppm)
08-91113	nd
08-91113	nd
Average	n/a
Std Dev	n/a
RSD (%)	**n/a**

Sample	As (ppm)
08-91028	nd
08-91028	nd
Average	n/a
Std Dev	n/a
RSD	**n/a**

Sample	As (ppm)
08-91042	nd
08-91042	nd
Average	n/a
Std Dev	n/a
RSD (%)	**n/a**

08-91072	nd
08-91072	nd
Average	n/a
Std Dev	n/a
RSD (%)	**n/a**

08-91102	0.3
08-91102	0.3
Average	0.3
Std Dev	0.0
RSD (%)	**0**

08-91108	nd
08-91108	nd
Average	n/a
Std Dev	n/a
RSD (%)	**n/a**

08-91152	nd
08-91152	nd
Average	n/a
Std Dev	n/a
RSD (%)	**n/a**

08-91159	nd
08-91159	nd
Average	n/a
Std Dev	n/a
RSD (%)	**n/a**

08-91195	nd
08-91195	nd
Average	n/a
Std Dev	n/a
RSD (%)	**n/a**

08-91199	nd
08-91199	nd
Average	n/a
Std Dev	n/a
RSD (%)	**n/a**

08-91203	nd
08-91203	nd
Average	n/a
Std Dev	n/a
RSD (%)	**n/a**

08-91321	nd
08-91321	nd
Average	n/a
Std Dev	n/a
RSD (%)	**n/a**

08-91367	0.3
08-91367	0.4
Average	0.4
Std Dev	0.1
RSD (%)	**20**

nd = below laboratory detection limits (0.2 ppm)
n/a = calculation not applicable based on nd values

Appendix B: Sample Results

Table B-1: Total Arsenic Results for Samples Collected in the Nadina Forest District

Table B-2: Total Arsenic Results for Samples Collected in the Cascades Forest District

Table B-1: Total Arsenic Results for Samples Collected in the Nadina Forest District

Tree	DBH (cm)	Wood core sample #	Wood core As (ppm)		Soil sample #	Soil As (ppm)		Foliage sample #	Foliage As (ppm)	Foliage species
Site: 1000		**Location:** 5 km Gold FSR						**Year treated:** 2002 (estimated)		
Treated										
1	31.3	1000-1	1.6		1000-1-D	7.0		1000-1-D	nd	*Cornus canadensis*
					1000-1-F	4.1		1000-1-F	nd	*Cornus canadensis*
2	38.7	1000-2	2.2		1000-2-D	5.1		1000-2-D	nd	*Cornus canadensis*
					1000-2-F	3.8		1000-2-F	nd	*Cornus canadensis*
3	36.9	1000-3	5.4		1000-3-D	5.9		1000-3-D	nd	*Cornus canadensis*
					1000-3-F	5.1		1000-3-F	nd	*Cornus canadensis*
Control										
4	34.3	1000-4	nd		1000-4-D	3.9		1000-4-D	nd	*Cornus canadensis*
5	44.8	1000-5	nd		1000-5-D	5.1		1000-5-D	nd	*Cornus canadensis*
Site: 2586		**Location:** 5 km Gold FSR						**Year treated:** 2002		
Treated										
1	34	2586-1	43.1		2586-1-D	8.9		2586-1-D	0.3	*Cornus canadensis*
					2586-1-F	2.5		2586-1-F	nd	*Cornus canadensis*
2	44.5	2586-2	1.8		2586-2-D	4.4		2586-2-D	nd	*Cornus canadensis*
					2586-2-F	6.6		2586-2-F	nd	*Cornus canadensis*
3	32.7	2586-3	3.4		2586-3-D	3.1		2586-3-D	nd	*Cornus canadensis*
					2586-3-F	4.5		2586-3-F	nd	*Cornus canadensis*
Control										
4	29.6	2586-4	nd		2586-4-D	2.7		2586-4-D	nd	*Cornus canadensis*
5	31.9	2586-5	nd		2586-5-D	3.9		2586-5-D	nd	*Cornus canadensis*
Site: 2737		**Location:** 11km Old Chisholm FSR						**Year treated:** 1999		
Treated										
1	34.0	2737-1	20.6		2737-1-D	3.4		2737-1-D	0.2	*Epilobium angustifolium*
					2737-1 F	2.3		2737-1-D	nd	*Cornus canadensis*
								2737-1-F	nd	*Epilobium angustifolium*
								2737-1-F	nd	*Cornus canadensis*
2	36.7	2737-2	3		2737-2-D	2.2		2737-2-D	0.3	*Epilobium angustifolium*
					2737-2-F	2.1		2737-2-D	nd	*Cornus canadensis*
								2737-2-F	nd	*Epilobium angustifolium*
								2737-2-F	nd	*Cornus canadensis*
3	33.4	2737-3	6.7		2737-3-D	2.2		2737-3-D	nd	*Epilobium angustifolium*
					2737-3-F	3.4		2737-3-D	nd	*Cornus canadensis*
								2737-3-F	nd	*Epilobium angustifolium*
								2737-3-F	nd	*Cornus canadensis*
Control										
4	35.8	2737-4	nd		2737-4-D	2.6		2737-4-D	nd	*Epilobium angustifolium*
								2737-4-D	nd	*Cornus canadensis*
5	49.5	2737-5	nd		2737-5-D	1.8		2737-5-D	nd	*Epilobium angustifolium*
								2737-5-D	nd	*Cornus canadensis*

nd = below analytical detection limits (0.2 ppm)

Table B-1: Total Arsenic Results for Samples Collected in the Nadina Forest District (continued)

Tree	DBH (cm)	Wood core sample #	Wood core As (ppm)		Soil sample #	Soil As (ppm)		Foliage sample #	Foliage As (ppm)	Foliage species
Site: 2748		**Location:** 11km Old Chisholm FSR						**Year treated:** 1999		
Treated										
1	48.2	2748-1	1.4		2748-1-D	6.2		2748-1-D	0.7	*Epilobium angustifolium*
					2748-1-F	6.7		2748-1-D	nd	*Aster spp*
								2748-1-F	nd	*Epilobium angustifolium*
								2748-1-F	nd	*Aster spp*
3	48.7	2748-3	1.3		2748-3-D	4.6		2748-3-D	nd	*Epilobium angustifolium*
					2748-3-F	3.6		2748-3-D	0.3	*Aster spp*
								2748-3-F	nd	*Epilobium angustifolium*
								2748-3-F	nd	*Aster spp*
4	27.7	2748-4	1.8		2748-4-D	6.5		2748-4-D	nd	*Epilobium angustifolium*
					2748-4-F	3.4		2748-4-D	nd	*Aster spp*
								2748-4-F	nd	*Epilobium angustifolium*
								2748-4-F	nd	*Aster spp*
Control										
2	44.5	2748-2	nd		2748-2-D	3.2		2748-2-D	nd	*Epilobium angustifolium*
								2748-2-D	nd	*Aster spp*
5	25.0	2748-5	nd		2748-5-D	2.9		2748-5-D	nd	*Epilobium angustifolium*
								2748-5-D	nd	*Aster spp*
Site: 4357		**Location:** Buck Flats Rd.						**Year treated:** 2002		
Treated										
1	32.8	4357-1	9.0		4357-1-F	6.0				
					4357-1-D	8.9				
2	30.3	4357-2	18.3		4357-2-F	9.6				
					4357-2-D	5.8				
3	29.7	4357-3	7.4		4357-3-F	5.8				
					4357-3-D	5.2				
Control										
4	32.9	4357-4	nd		4357-4-D	6.9				
5	29.7	4357-5	nd		4357-5-D	4.2				
Site: 5198		**Location:** Babine Lake island, east of Granisle						**Year treated:** 2001		
Treated										
1	37.2	5198-1	11.4		5198-1-D	10.3		5198-1-D	0.3	*Cornus canadensis*
					5198-1-F	8.8		5198-1-F	nd	*Cornus canadensis*
2	41.0	5198-2	1.3		5198-2-D	9.6		5198-2-D	nd	*Cornus canadensis*
					5198-2-F	9.8		5198-2-F	nd	*Cornus canadensis*
3	39.1	5198-3	0.7		5198-3-D	8.4		5198-3-D	nd	*Cornus canadensis*
					5198-3-F	6.3		5198-3-F	nd	*Cornus canadensis*
Control										
4	34.5	5198-4	nd		5198-4	2.0		5198-4	nd	*Cornus canadensis*
5	41.3	5198-5	nd		5198-5	4.0		5198-5	nd	*Cornus canadensis*

nd = below analytical detection limits (0.2 ppm)

Table B-1: Total Arsenic Results for Samples Collected in the Nadina Forest District (continued)

Tree	DBH (cm)	Wood core sample #	Wood core As (ppm)		Soil sample #	Soil As (ppm)		Foliage sample #	Foliage As (ppm)	Foliage species
Site: 7410		**Location:** 67 km Morice River FSR						**Year treated:** 2003		
Treated										
1	31.4	7410-1	10.1		7410-1-D	4.1		7410-1-D	nd	*Epilobium angustifolium*
					7410-1-F	3.3		7410-1-F	nd	*Epilobium angustifolium*
2	19.9	7410-2	22.8		7410-2-D	3.5		7410-2-D	nd	*Epilobium angustifolium*
					7410-2-F	4.5		7410-2-F	nd	*Epilobium angustifolium*
3	27.2	7410-3	15		7410-3-D	6.1		7410-3-D	nd	*Epilobium angustifolium*
					7410-3-F	5.4		7410-3-F	nd	*Epilobium angustifolium*
Control										
4	27.7	7410-4	nd		7410-4-D	7.1		7410-4-D	nd	*Epilobium angustifolium*
5	23.0	7410-5	nd		7410-5-D	2.0		7410-5-D	nd	*Epilobium angustifolium*
Site: 7599		**Location:** 5 km Gold FSR						**Year treated:** 2003		
Treated										
1	40.1	7599-1	2.4		7599-1-D	3.9		7599-1-D	0.4	*Aster spp.*
					7599-1-F	5.5		7599-1-F	nd	*Aster spp.*
2	30.8	7599-2	2.8		7599-2-D	4.2		7599-2-D	nd	*Aster spp.*
					7599-2-F	2.8		7599-2-F	nd	*Aster spp.*
3	34.7	7599-3	32.7		7599-3-D	3.7		7599-3-D	nd	*Aster spp.*
					7599-3-F	3.7		7599-3-F	nd	*Aster spp.*
Control										
4	34.7	7599-4	nd		7599-4-D	3.1		7599-4-D	nd	*Aster spp.*
5	36.7	7599-5	nd		7599-5-D	2.4		7599-5-D	nd	*Aster spp.*
Site: 7603		**Location:** 5 km Gold FSR						**Year treated:** 2003		
Treated										
1	49.5	7603-1	2.2		7603-1-D	4.5		7603-1-D	nd	*Aster spp.*
					7603-1-F	2.3		7603-1-F	nd	*Aster spp.*
2	40.3	7603-2	54.8		7603-2-D	2.4		7603-2-D	0.9	*Aster spp.*
					7603-2-F	4.2		7603-2-F	nd	*Aster spp.*
3	41.7	7603-3	nd		7603-3-D	2.9		7603-3-D	nd	*Aster spp.*
					7603-3-F	4.1		7603-3-F	nd	*Aster spp.*
Control										
4	21.5	7603-4	nd		7603-4-D	3.6		7603-4-D	nd	*Aster spp.*
5	18.7	7603-5-D	0.5		7603-5-D	2.8		7603-5-D	nd	*Aster spp.*
Site: 630D		**Location:** Francois Lake (Noralee)						**Year treated:** 2001		
Treated										
1	31.1	630D-1	18.5		630D-1-D	2.4		630D-1-D	0.3	*Epilobium angustifolium*
					630D-1-F	1.8		630D-1-F	nd	*Epilobium angustifolium*
2	27.8	630D-2	1.1		630D-2-D	3.2		630D-2-D	nd	*Epilobium angustifolium*
					630D-2-F	2.3		630D-2-F	nd	*Epilobium angustifolium*
4	27.7	630D-4	2.2		630D-4-D	2.8		630D-4-D	0.4	*Epilobium angustifolium*
					630D-4-F	4		630D-4-F	nd	*Epilobium angustifolium*
Control										
3	28.2	630D-3	nd		630D-3-D	1.4		630D-3-D	nd	*Epilobium angustifolium*
5	24.1	630D-5	nd		630D-5-D	1.2		630D-5-D	nd	*Epilobium angustifolium*

nd = below analytical detection limits (0.2 ppm)

Table B-2: Total Arsenic Results for Samples Collected in the Cascades Forest District

Tree	DBH (cm)	Wood core sample #	Wood core As (ppm)		Soil sample #	Soil As (ppm)		Foliage sample #	Foliage As (ppm)	Foliage species
Site: A-11		**Location:** Helmer Rd.						**Year treated:** 1999		
Treated										
1	20.0	A-11-1	5.9		A-11-1-D	8.2				
					A-11-1-F	4.8				
2	21.2	A-11-2	30.8		A-11-2-D	4.5				
					A-11-2-F	4.8				
3	22.7	A-11-3	25.2		A-11-3-D	5.3				
					A-11-3-F	3.7				
Control										
4	19.6	A-11-4	nd		A-11-4-D	6.8				
5	23.1	A-11-5	nd		A-11-5-D	5.1				
Site: G-21		**Location:** Boss Lk.						**Year treated:** 2002		
Treated										
1	32.2	G21-1	0.8		G21-1D	1.1		G21-1D	0.4	*Mitella spp.*
					G21-1F	1.0				
2	28.3	G21-2	2.8		G21-2D	0.9		G21-2D	0.4	*Mitella spp.*
					G21-2F	0.9				
3	33.1	G21-3	14.7		G21-3D	1.4		G21-3F	nd	*Chimaphila umbellata*
					G21-3F	1.0				
Control										
4	29.6	G21-4	nd		G21-4D	1.5				
5	31.8	G21-5	nd		G21-5D	1.8		G21-5D	nd	*Chimaphila umbellata*
Site: G-31		**Location:** Boss Lk.						**Year treated:** 1999		
Treated										
1	29.7	G31-1	8.7		G31-1-D	1.7		G31-1D	0.3	*Cornus canadensis*
					G31-1-F	1.6		G31-1F	nd	*Cornus canadensis*
2	41.5	G31-2	11.9		G31-2-D	1.8		G31-2D	0.7	*Cornus canadensis*
					G31-2-F	2.3		G31-2F	nd	*Cornus canadensis*
3	40.7	G31-3	6.6		G31-3-D	1.5		G31-3D	nd	*Cornus canadensis*
					G31-3-F	1.3		G31-3F	nd	*Cornus canadensis*
Control										
4	27.0	G31-4	nd		G31-4-D	1.3		G31-4D	nd	*Chimaphila umbellata*
5	23.1	G31-5	nd		G31-5-D	0.8				
Site: J-21		**Location:** Otter Rd./Thalia Lk.						**Year treated:** 2002		
Treated										
1	21.1	J-21-1	1.1		J-21-1-D	4.2				
					J-21-1-F	3.4				
2	27.7	J-21-2	1.3		J-21-2-D	3.7				
					J-21-2-F	5.4				
3	30.6	J-21-3	7.9		J-21-3-D	4.4				
					J-21-3-F	2.6				
Control										
4	20.9	J-21-4	1.5		J-21-4-D	2.8				
5	26.3	J-21-5	nd		J-21-5-D	2.4				

nd = below analytical detection limits (0.2 ppm)

Table B-2: Total Arsenic Results for Samples Collected in the Cascades Forest District (continued)

Tree	DBH (cm)	Wood core sample #	Wood core As (ppm)	Soil sample #	Soil As (ppm)	Foliage sample #	Foliage As (ppm)	Foliage species
Site: J-11		**Location:** Otter Rd./Thalia Lk.				**Year treated:** 2002		
Treated								
1	29.6	J-11-1	14.7	J-11-1-D	30.2			
				J-11-1-F	3.5			
2	29.2	J-11-2	6.7	J-11-2-D	2.1			
				J-11-1-D-a	0.6			
				J-11-1-D-b	0.7			
				J-11-1-D-c	0.7			
				J-11-1-D-d	0.7			
				J-11-1-D-e	1.0			
				J-11-1-D-f	0.7			
				J-11-1-D-g	1.3			
			J-11-1-D-100 cm out		0.9			
				J-11-2-F	2.5			
3	34.5	J-11-3	13.4	J-11-3-D	4.6			
				J-11-3-F	2.2			
Control								
4	27.8	J-11-4	nd	J-11-4-D	2.4			
5	31.1	J-11-5	nd	J-11-5-D	2.4			
Site: L-11		**Location:** Princeton Hwy Allison Lk. North				**Year treated:** 1999		
Treated								
1	24.2	L11-1	25.0	L11-1D	1.9	L11-1D	nd	*Mahonia aquifolium*
				L11-1F	1.8	L11-1F	nd	*Mahonia aquifolium*
2	23.2	L11-2	6.7	L11-2D	1.7			
				L11-2F	1.7			
3	31.4	L11-3	9.4	L11-3D	3.4	L11-3D	0.2	*Mahonia aquifolium*
				L11-3F	2.5	L11-3F	nd	*Mahonia aquifolium*
Control								
4	22.6	L11-4	nd	L11-4D	2.8			
5	26.1	L11-5	nd	L11-5D	2.9	L11-5D	nd	*Mahonia aquifolium*
Site: L-31		**Location:** Princeton Hwy Allison Lk. North				**Year treated:** 1999		
Treated								
1	29.1	L31-1	nd	L31-1-D	2.7			
				L31-1-F	2.6			
2	15.9	L31-2	6.5	L31-2-D	2.6			
				L31-2-F	1.6			
3	17.5	L31-3	nd	L31-3-D	62.3	L31-3	0.4	*Arctostaphylos uva-ursi*
			L31-3-D-15 cm depth		0.7			
			L31-3-D-50 cm out		0.7			
			L31-3-D-100 cm out		2.7			
				L31-3-D-a	0.4			
				L31-3-D-b	0.6			
				L31-3-D-c	0.6			
				L31-3-D-d	0.6			
				L31-3-F	0.7			
Control								
4	21.3	L31-4	nd	L31-4-D	1.5			
5	26.1	L31-5	nd	L31-5-D	1.5			

nd = below analytical detection limits (0.2 ppm)

Table B-2: Total Arsenic Results for Samples Collected in the Cascades Forest District (continued)

Tree	DBH (cm)	Wood core sample #	Wood core As (ppm)		Soil sample #	Soil As (ppm)		Foliage sample #	Foliage As (ppm)	Foliage species
Site: M-51		**Location:** Hornet FSR						**Year treated:** 1999		
Treated										
1	26.5	M-51-1	61.7		M-51-1-D	2.0				
					M-51-1-F	1.2				
2	17.9	M-51-2	50.9		M-51-2-D	2.3				
					M-51-2-F	1.5				
3	15.0	M-51-3	16.4		M-51-3-D	1.6				
					M-51-3-F	1.2				
Control										
4	21.4	M-51-4	nd		M-51-4-D	1.3				
5	22.6	M-51-5	nd		M-51-5-D	nd				
Site: Q-31		**Location:** Missezula Lk. North						**Year treated:** 2002		
Treated										
1	27.4	Q-31-1	0.8		Q-31-1-D	2.9				
					Q-31-1-F	3.2				
2	20.6	Q-31-2	nd		Q-31-2-D	7.9				
					Q-31-2-F	4.4				
3	19.5	Q-31-3	0.9		Q-31-3-D	5.1		Q-31-3D	nd	*Not recorded*
					Q-31-3-F	3.8		Q-31-3F	nd	*Not recorded*
Control										
4	22.3	Q-31-4	nd		Q31-4-D	2.6				
5	22.5	Q-31-5	nd		Q31-5-D	2.1				
Site: Q-31A		**Location:** Missezula Lk. North						**Year treated:** 2002		
Treated										
1	22.1	Q31A-1	40.6		Q-31A-1-D	2.2				
					Q-31A-1-F	4.0				
2	22.7	Q31A-2	11.3		Q-31A-2-D	23.9				
					Q-31A-2-F	2.8				
3	21.5	Q31A-3	32.5		Q-31A-3-D	4.7				
					Q-31A-3-F	2.4				
Control										
4	18.9	Q-31A-4	nd		Q-31A-4-D	4.5				
5	20.4	Q-31A-5	nd		Q-31A-5-D	4.3				

nd = below analytical detection limits (0.2 ppm)

Appendix C: Calculations

Estimated volume of British Columbia (BC) soil around MSMA-treated trees containing arsenic levels above Canadian Council of Ministers of the Environment (CCME) soil quality guideline (SQG) of 12 ppm (Figure C-1)

Assumptions:

- Samples collected around tree L-31-3 can be used to estimate soil volumes and represent the worst-case scenario for elevated soil arsenic based on all samples collected;
- Arsenic levels decrease linearly from area of maximum concentration;
- Linear regression between adjacent sample arsenic levels can be used to estimate distance from maximum arsenic concentration where 12 ppm is encountered; and
- The volume of soil in excess of 12 ppm can be represented as a cylinder, with the maximum measured soil concentration (62 ppm in sample L-31-3-D) located on the surface at the centre of the cylinder.

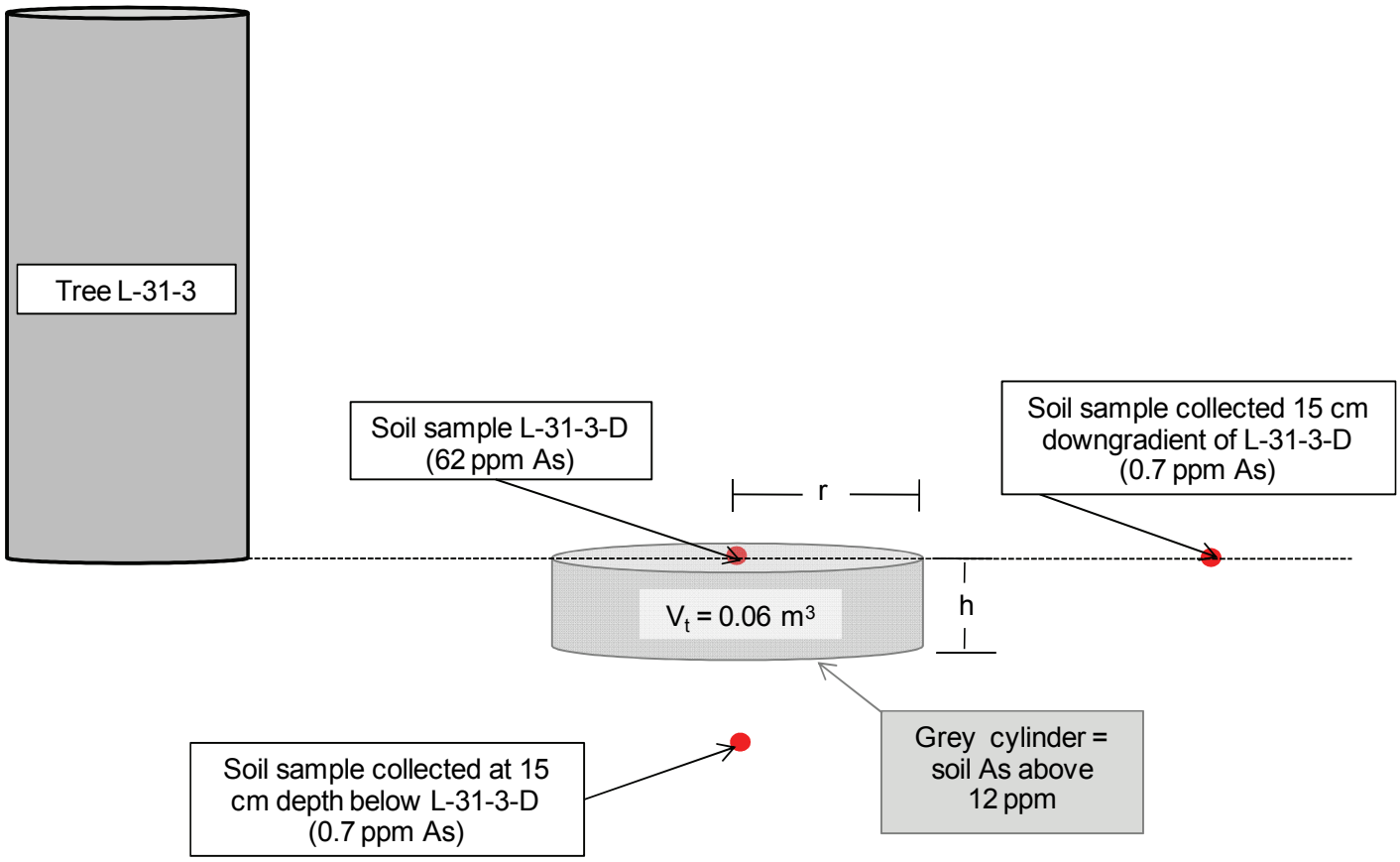


Figure C-1. Schematic representation of estimated volume of soil with arsenic levels in excess of 12 ppm associated with MSMA-treated tree L-31-3.

Step 1: Number of trees in BC with associated soil in excess of CCME SQG

Find: Approximate number of MSMA-treated trees in BC with soils in excess of 12 ppm (CCME SQG).

$$\mathbf{T_{ea} = \frac{T_{sea}}{T_{st}} = \frac{3}{60} x\ 100 = 5\%} \qquad \textbf{Equation 1}$$

$$\mathbf{T_{bc} = T_t\ x\ T_{ea} = 150\ 000\ x\ 5\% = 7,500\ trees} \qquad \textbf{Equation 2}$$

Where:

T_{ea} = Estimated proportion of treated trees with elevated soil arsenic (%)

T_{sea} = Total number of treated trees sampled with soil arsenic levels exceeding 12 ppm

T_{st} = Total number of treated trees sampled in the Nadina and Cascades districts

T_{bc} = Approximate number of trees with elevated arsenic in BC

T_t = Estimated total number of MSMA-treated trees in BC

Step 2: Worst-case volume of soil in excess of CCME SQG

Find: Volume of soil with arsenic levels above 12 ppm (CCME SQG) associated with all MSMA-treated trees in British Columbia.

$$\mathbf{V_t = \pi r^2 h = \pi(0.4\ m)^2(0.1\ m) = 0.1\ m^3} \qquad \textbf{Equation 3}$$

$$\mathbf{V_{bc} = V_t\ x\ T_{bc}\ = 0.1\ m^3\ x\ 7500 = 450\ m^3} \qquad \textbf{Equation 4}$$

Where:

SQG_{as} = CCME soil quality guideline for arsenic (12 ppm)

r = Horizontal distance between maximum soil arsenic and 12 ppm level estimated using linear regression between sample points (Figure C-1)

h = Vertical distance between maximum soil arsenic and 12 ppm level estimated using linear regression between sample points (Figure C-1)

V_t = Estimated volume of soil per MSMA-treated tree with arsenic above 12 ppm

V_{bc} = Estimated total volume of soil in British Columbia with arsenic above 12 ppm associated with MSMA-treated trees

T_{bc} = Approximate number of trees with elevated arsenic in BC

Step 3: Worst-case soil area in excess of CCME SQG

Find: Percent of forested area in BC treated with MSMA that could have soil with arsenic levels above 12 ppm (CCME SQG).

$$\mathbf{a_s = \pi r^2 x\ T_{bc} = \pi(0.4\ m)^2\ x\ 7500 = 4000\ m^2 = 0.4\ ha} \qquad \textbf{Equation 5}$$

$$\mathbf{a_t = \frac{T_t}{n_t} = \frac{150\ 000\ trees}{890\ trees/ha} = 170\ ha} \qquad \textbf{Equation 6}$$

$$\mathbf{a_{bc} = \frac{a_s}{a_t}\ x\ 100 = \frac{0.4\ ha}{170\ ha} x\ 100 = 0.2\ \%} \qquad \textbf{Equation 7}$$

Where:

a_s = Estimated area of soil per MSMA-treated tree with arsenic above 12 ppm

r = Horizontal distance between maximum soil arsenic and 12 ppm level

T_{bc} = Approximate number of trees with elevated arsenic in BC

a_t = Estimated area of forested land in BC associated with MSMA-treated trees

T_t = Estimated total number of MSMA-treated trees in BC

n_t = Number of mature lodgepole pine per hectare (average of overstory density values in Nigh *et al.* 2008)

a_{bc} = Estimated percent forested area in BC that could have soil in excess of 12 ppm

Hypothetical worst-case scenario arsenic levels in soil if an MSMA-treated tree were to fall to the forest floor and decompose in-situ.

Assumptions:

- Tree M-51-1 (62 ppm arsenic) in the Cascades Forest District is representative of the maximum arsenic levels found in the wood of MSMA-treated trees in British Columbia;
- The majority of MSMA-derived arsenic applied to the base of the tree in the axe frill is concentrated between 0-2 m trunk height and in the outer 2 cm of the conductive tissue of the tree (phloem and outer xylem). This assumption is supported by the published research of Maclauchlan *et al.* (1987, 1988) and Manville *et al.* (1988). Phloem thickness was estimated using Cole (1973);
- The lower 2 m of the trunk can be represented by a cylinder with a diameter equal to diameter at breast height (DBH; Figure C-2);
- The upper portion of the tree can be represented by a cone with a base equal to DBH;
- All of the arsenic in tree M-51-1 goes directly into the soil, dilution from the addition of decomposing wood tissue is not considered.

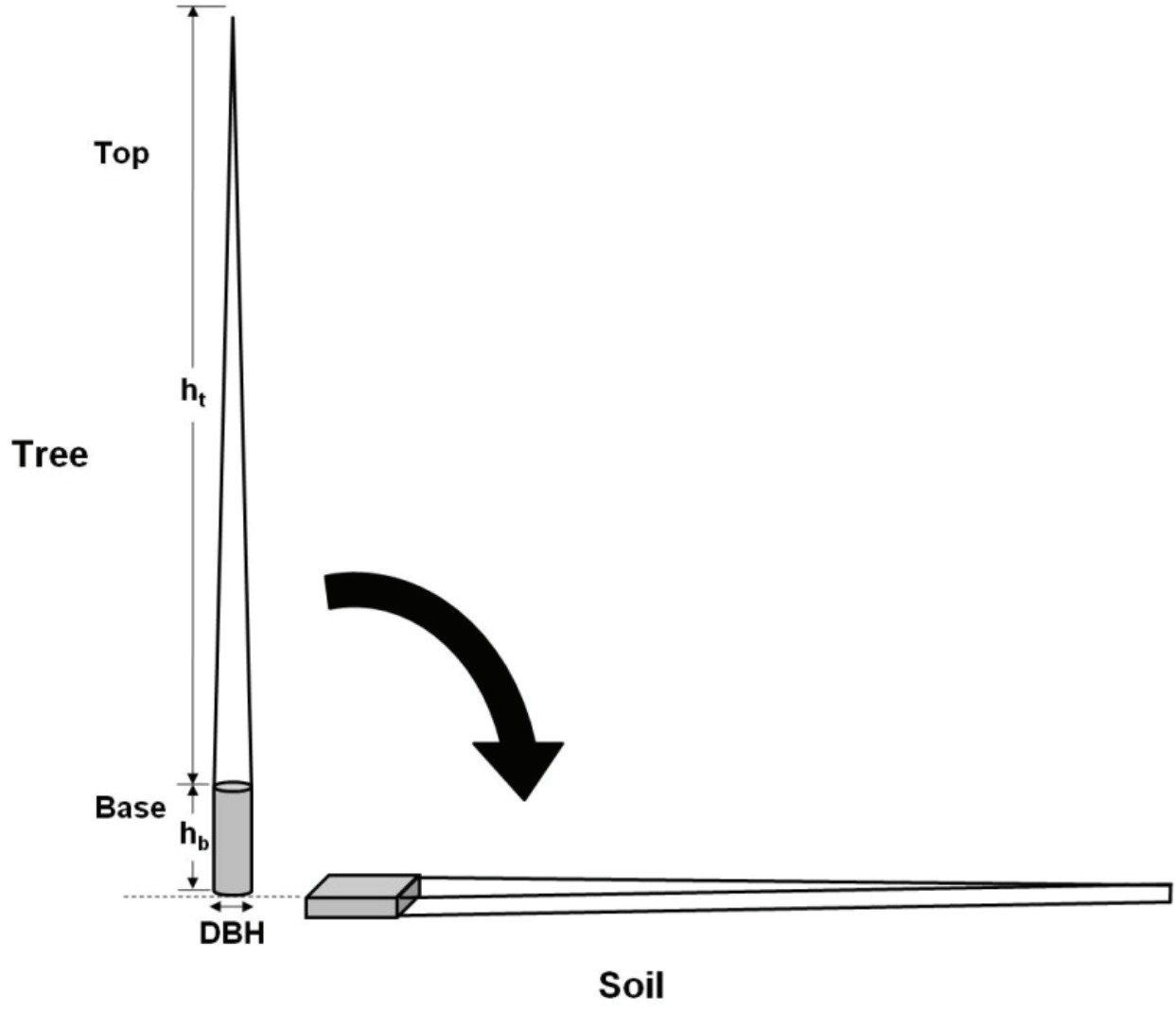


Figure C-2. Schematic of the model used to estimate soil arsenic levels from the decomposition of MSMA-treated tree M-51-1.

Step 1: Total amount of arsenic in tree M-51-1

Find: Find the mass of wood in tree M-51-1.

Total mass of tree trunk:

$$\mathbf{M_T = a2r_T^b \rho_{LP} = 1.1x10^{-4}(27\ cm)^{2.56}(430\ kg/m^3) = 204\ kg} \qquad \textbf{Equation 8}$$

Mass of tree base:

$$\mathbf{M_{Tbase} = \pi r_T^2 h_b \rho_{LP} = \pi(0.1\ m)^2(2.0\ m)(430\ kg/m^3) = 47\ kg} \qquad \textbf{Equation 9}$$

$$\mathbf{M_{Ibase} = \pi r_I^2 h_b \rho_{LP} = \pi(0.1\ m)^2(2.0\ m)(430\ kg/m^3) = 41\ kg} \qquad \textbf{Equation 10}$$

$$\mathbf{M_{Obase} = M_{Tbase} - M_{Ibase} = 47\ kg - 41\ kg = 6.9\ kg} \qquad \textbf{Equation 11}$$

Mass of tree top:

$$\mathbf{M_{Ttop} = M_T - M_{Tbase} = 204\ kg - 47\ kg = 160\ kg} \qquad \textbf{Equation 12}$$

Where:

M_T = Total mass M-51-1 tree trunk

M_{Tbase} = Total mass of the lower 2 m of the trunk of tree M-51-1

M_{Ibase} = Mass of the inner sapwood of the lower trunk (inner xylem and heartwood)

M_{Obase} = Mass of the outer 2 cm of the lower trunk (phloem and outer xylem)

M_{Ttop} = Mass of the trunk top of tree M-51-1

[1]ppm is equivalent to mg/kg

h_b = Height of lower portion of trunk (2 m)

ρ_{LP} = Density of air-dried lodgepole pine (BC FII 2009)

a,b = Constants derived for *Pinus* spp. (Zianis *et al.,* 2005)

r_T = Total radius of lower 2m of trunk derived from DBH

r_I = Total radius of inner sapwood of trunk

Find: The mass of arsenic in the trunk of tree M-51-1.

$$\mathbf{M_{Asbase}} = (\mathbf{M_{Obase}C_{Obase}}) + (\mathbf{M_{Ibase}C_{Ibase}}) \qquad \textbf{Equation 13}$$

$$= (\mathbf{6.9\ kg\ x\ 62\ mg/kg}) + (\mathbf{41\ kg\ x\ 5.0\ mg/kg}) \ = \mathbf{630\ mg}$$

$$\mathbf{M_{Astop}} = (\mathbf{M_{Ttop}C_{Ttop}}) = (\mathbf{160\ kg\ x\ 5.0\ mg/kg}) = \mathbf{780\ mg} \qquad \textbf{Equation 14}$$

Where:

M_{Asbase}= Total mass of arsenic in the lower 2 m of the trunk of tree M-51-1

C_{Obase} = Concentration of arsenic in the outer 2 cm of the trunk (phloem and outer xylem), estimated to be equivalent to the concentration measured in the wood tissue sample from M-51-1 (62 ppm[1])

C_{Ibase} = Concentration of arsenic in the inner sapwood of the trunk (inner xylem and heartwood), estimated from Maclauchlan *et al.* (1997, 1998)

M_{Astop} = Total mass of arsenic in the top of the trunk of tree M-51-1

C_{Ttop} = Concentration of arsenic in the top of the trunk, estimated from Maclauchlan *et al.* (1997, 1998) and Manville *et al.* (1988)

[1]ppm is equivalent to mg/kg

Step 2: Total amount of arsenic in soil from tree M-51-1

Find: The potential volume of soil impacted by arsenic released during the decomposition of MSMA-treated tree M-51-1.

$$\mathbf{V_{sbase} = h_b 2 r_T d = (2.0\ m)(2\ x\ 0.1\ m)(0.1\ m) = 0.1\ m^3} \qquad \textbf{Equation 15}$$

$$\mathbf{V_{stop} = \frac{1}{2}[h_t 2 r_T d] = \frac{1}{2}[(15\ m)(2\ x\ 0.1\ m)(0.1\ m)] = 0.2\ m^3} \qquad \textbf{Equation 16}$$

Where:

V_{sbase} = Potential volume of soil impacted by arsenic released during decomposition of the lower 2 m of tree M-51-1

V_{stop} = Potential volume of soil impacted by arsenic released during decomposition of the top of tree M-51-1

d = Estimated depth of impacted soil (0.1 m)

h_t = Height of the upper portion of tree M-51-1, estimated using equations derived for *Pinus* spp. (Zianis *et al.,* 2005) and subtracting h_b

Find: Soil arsenic concentrations for soil potentially impacted by arsenic released during the decomposition of MSMA-treated tree M-51-1, considering two different soil scenarios (silt loam, duff).

Scenario 1: Silt loam

$$\mathbf{C_{Asbase(SL)} = \frac{M_{Asbase}}{V_{sbase}\rho_{sl}} + C_b} \qquad \textbf{Equation 17}$$

$$= \frac{\mathbf{627\ mg}}{(\mathbf{0.1\ m^3})\left(\mathbf{1200\ {}^{kg}/_{m^3}}\right)} + \mathbf{0.8\ {}^{mg}/_{kg} = 11\ ppm}$$

$$\mathbf{C_{Astop(SL)} = \frac{M_{Astop}}{V_{stop}\rho_{sl}} + C_b} \qquad \textbf{Equation 18}$$

$$= \frac{\mathbf{780\ mg}}{(\mathbf{0.2\ m^3})\left(\mathbf{1200\ {}^{kg}/_{m^3}}\right)} + \mathbf{0.8\ {}^{mg}/_{kg} \quad = 4.1\ ppm}$$

Scenario 2: Lodgepole pine duff

$$\mathbf{C_{Asbase} = \frac{M_{Asbase}}{V_{sbase}\rho_{d}} + C_b} \qquad \textbf{Equation 19}$$

$$= \frac{\mathbf{630\ mg}}{(\mathbf{0.1\ m^3})\left(\mathbf{200\ {}^{kg}/_{m^3}}\right)} + \mathbf{0.8\ {}^{mg}/_{kg} = 60.0\ ppm}$$

$$\mathbf{C_{Astop}} = \frac{\mathbf{M_{Astop}}}{\mathbf{V_{stop}\rho_d}} + \mathbf{C_b} \qquad \textbf{Equation 20}$$

$$= \frac{\mathbf{780\ mg}}{(\mathbf{0.2\ m^3})\left(\mathbf{200\ {}^{kg}/_{m^3}}\right)} + \mathbf{0.8\ {}^{mg}/_{kg}} = \mathbf{21\ ppm}$$

Where:

C_{Asbase} = Potential concentration of arsenic in soil from the lower 2 m of tree M-51-1 for silt loam (SL) and duff (d)

C_{Astop} = Potential concentration of arsenic in soil from the top of tree M-51-1 for SL and d

ρ_{sl} = Bulk density of silt loam (Pedosphere, 2009)

ρ_{sl} = Bulk density of lodgepole pine duff (Hirsch and Pengelly, 1999)

C_b = Average background arsenic concentrations for site M-51(soil samples collected around control trees)

Estimated volume of soil in BC containing arsenic associated with in-situ *decomposition of MSMA-treated trees at levels above CCME SQGs*

Assumptions:

- Soil volumes exceeding SQGs estimated from measured arsenic concentrations for wood cores are representative of province-wide conditions;
- Lodgepole pine duff is representative of the surface soil horizon throughout MSMA-treated stands in British Columbia.

Find: Find the volume of soil in BC exceeding CCME SQGs.

$$\mathbf{V_{ave} = \frac{V_e}{T_e} = \frac{3.3 m^3}{23} = 0.1\ m^3/tree} \qquad \textbf{Equation 21}$$

$$\mathbf{V_{BC} = T_T p_e V_{ave} = (150,000)(38\%)(0.1\ m^3/tree) = 8200\ m^3} \qquad \textbf{Equation 22}$$

Where:

V_{ave} = Average volume of soil exceeding CCME SQGs for arsenic (12 ppm) per MSMA-treated tree

V_e = Total volume of soil exceeding 12 ppm arsenic estimated from wood core samples. Estimated by applying equations 7-18 to all wood cores collected from MSMA-treated trees in the Nadina and Cascades Forest Districts and taking the sum of all soil volumes with arsenic concentrations greater than or equal to 12 ppm

T_e = Number of MSMA-treated trees in the Nadina and Cascades Forest Districts with arsenic in excess of the SQG associated with *in-situ* decomposition

V_{BC} = Total volume of soil in BC exceeding with arsenic in excess of SQG associated with *in-situ* decomposition of MSMA-treated trees

T_t = Estimated total number of MSMA-treated trees in BC

P_e = Percentage of MSMA-treated trees sampled in the Nadina and Cascades Forest Districts with arsenic in excess of SQG associated with *in-situ* decomposition

Appendix D. Human Health Risk Assessment Calculations

Estimated daily intake of arsenic for soil or food ingestion:

$$\mathbf{EDI}\left(\frac{\mathbf{mg}}{\mathbf{kg\ d}}\right) = \frac{\mathbf{EPC\ x\ IR_{s/f}\ x\ RAF_{oral}\ x\ ET_1\ x\ EF\ x\ CF_1\ x\ ED}}{\mathbf{BW\ x\ AT}} \qquad \textbf{Equation 23}$$

Where:

EPC = exposure point concentration (mg/kg)

$IR_{s/f}$ = ingestion rate of soil (g/d) or ingestion rate of food (g/d)

RAF_{oral} = relative absorption factor for oral ingestion (unitless)

ET_1 = exposure time (days spent on site/seven days)

EF = exposure frequency (weeks spent on site/52 weeks)

CF_1 = unit conversion factor (1E-03kg/g)

ED = exposure duration (years) – to be used for carcinogenic chemicals of potential concern (CoPCs) only

BW = body weight of receptor (kg)

AT = averaging time (years) – to be used for carcinogenic CoPCs only

Note: Exposure duration (ED) is the total number of years the receptor is exposed to the site and the averaging time (AT) is the life expectancy of the receptor. The scenarios used to estimate exposure to arsenic from MSMA-treated trees assumed that the receptor was visiting the site for their entire lifetime. Therefore, ED and AT will cancel each other out, but have been included in the calculations for completeness.

Estimated daily intake of arsenic for dermal contact with soil:

$$\mathbf{EDI}\ \left(\frac{\mathbf{mg}}{\mathbf{kg\ d}}\right) = \frac{(\mathbf{EPC\ x\ SA_h\ xSAF_h}) + (\mathbf{EPC\ x\ SA_o\ x\ SAF_o})\ \mathbf{x\ RAF_{derm}\ x\ ET_1\ x\ EF\ x\ CF_1\ x\ ED}}{\mathbf{BW\ x\ AT}} \quad \textbf{Equation 24}$$

For dermal contact with wood for forestry worker assumption is that SAF and SA are equal to that of soil for manual labourer.

Where:

EPC = exposure point concentration (mg/kg)

SA_h = surface area - hand (cm^2)

SAF_h = soil adherence factor -hand (g/cm^2*d)

SA_o = surface area – other than hand (cm^2)

SAF_o = soil adherence factor – other than hand (g/cm^2*d)

RAF_{derm} = relative absorption factor of dermal contact (unitless)

ET_1 = exposure time (days spent on site/seven days)

EF = exposure frequency (weeks spent on site/52 weeks)

CF_1 = unit conversion factor (1E-03kg/g)

ED = exposure duration (total years spent on site) – to be used for carcinogenic CoPCs only

BW = body weight of receptor (kg)

AT = averaging time (equal to ED) (years) – to be used for carcinogenic CoPCs only

Estimated daily intake of arsenic for inhalation of soil particles:

$$\mathbf{EDI}\left(\frac{\mathbf{mg}}{\mathbf{kg\ d}}\right) = \frac{\mathbf{EPC\ x\ P_A\ x\ IR_A\ x\ RAF_{inh}\ x\ ET_1\ x\ ET_2\ x\ EF\ x\ ED}}{\mathbf{BW\ x\ AT}} \qquad \textbf{Equation 25}$$

Where:

EPC = exposure point concentration (mg/kg)

ET_1 = exposure time (days spent on site/7days)

ET_2 = exposure time (hours spent on site/24hrs)

EF = exposure frequency (weeks spent on site/52 weeks)

ED = exposure duration (total years spent on site) – to be used for carcinogenic CoPCs only

BW = body weight of receptor (kg)

AT = averaging time (equal to ED) (years) – to be used for carcinogenic CoPCs only

IR_A = inhalation rate of (m^3/d)

P_A = particulate concentration in air (kg/m^3; $7.6x10^{-10}$ taken from Health Canada, 2007)

RAF_{inh} = relative absorption factor by inhalation (unitless)

Risk for non-carcinogenic arsenic:

$$\mathbf{HQ} = \frac{\mathbf{EDI}}{\mathbf{TDI}} \qquad \textbf{Equation 26}$$

Where:

HQ = hazard quotient from all site-specific intake pathways

EDI = estimated daily intake (mg/kg-d)

TDI = tolerable daily intake (mg/kg-d) (acute or chronic value used as described in text)

Risk for carcinogenic arsenic:

$$\mathbf{ILCR} = \mathbf{LADD\ x\ CSF} \qquad \textbf{Equation 27}$$

Where:

ILCR = incremental lifetime cancer risk (unitless)

LADD = lifetime average daily intake (mg/k-d) = estimated daily intake using ED and AT

CSF = cancer slope factor $(mg/kg\text{-}d)^{-1}$

Worked Examples

Non-carcinogenic risk to an adult hiker receptor including food ingestion

Soil Ingestion

$$\mathbf{EDI_{soil}} = \frac{\mathbf{EPC \times IR_s \times RAF_{oral} \times ET_1 \times EF \times CF_1}}{\mathbf{BW}} \qquad \textbf{Equation 28}$$

$$= \frac{(62\,\frac{mg}{kg})(0.02g/d)(1)(5\,\frac{d}{7d})(1\,\frac{wk}{52wk})(1E-03\,\frac{kg}{g})}{70.7\,kg}$$

$$= 2.4 \times 10^{-7} mg/kg\,d$$

Food consumption

$$\mathbf{EDI_{food}} = \frac{\mathbf{EPC \times IR_f \times RAF_{oral} \times ET_1 \times EF \times CF_1}}{\mathbf{BW}} \qquad \textbf{Equation 29}$$

$$= \frac{(0.9\,\frac{mg}{kg})(137g/d)(1)(5\,\frac{d}{7d})(1\,\frac{wk}{52wk})(1E-03\,\frac{kg}{g})}{70.7\,kg}$$

$$= 2.4 \times 10^{-5} mg/kg\,d$$

Dermal contact with soil

$$\mathbf{EDI_{dermal}} = \frac{(\mathbf{EPC \times SA_h \times SAF_h}) + (\mathbf{EPC \times SA_o \times SAF_o}) \times \mathbf{RAF_{derm} \times ET_1 \times EF \times CF_1 \times ED}}{\mathbf{BW \times AT}} \qquad \textbf{Equation 30}$$

$$= \frac{\left(62\,\frac{mg}{kg} \times 890cm^2 \times 1.00E-4\,\frac{g}{cm^2 d}\right) + \left(62\,\frac{mg}{kg} \times 8220cm^2 \times 1.00E-5\,\frac{g}{cm^2 d}\right) \times 0.03 \times (5\,\frac{d}{7d})(1\,\frac{wk}{52wk})(1E-03\,\frac{kg}{g})}{70.7kg}$$

$$= 6.2 \times 10^{-8} mg/kg\,d$$

Inhalation of Soil Particles

$$\mathbf{EDI_{inhalation}} = \frac{\mathbf{EPC\ x\ P_A\ x\ IR_A\ x\ RAF_{inh}\ x\ ET_1\ x\ ET_2\ x\ EF\ x\ ED}}{\mathbf{BW\ x\ AT}} \qquad \textbf{Equation 31}$$

$$= \frac{62\,\frac{mg}{kg}\ x\ 7.6x10^{-10}kg/m^3\ x\ 15.8\,\frac{m^3}{d}\ x\ 1\ x\ (5\,\frac{d}{7d})(6\,\frac{h}{24h})(1\,\frac{wk}{52wk})}{70.7kg}$$

$$= 3.6\ x\ 10^{-11}mg/kg\ d$$

Hazard Quotient

$EDI_{total} = EDI_{soil\ ingestion} + EDI_{food\ ingestion} + EDI_{dermal\ contact}$

A hazard quotient was not calculated based on exposure to arsenic from the inhalation exposure route because a TDI is not available for this pathway. The $EDI_{inhalation}$ was calculated for each scenario but was consistently orders of magnitude lower than the EDI for ingestion and dermal exposures. Therefore, this exposure route was deemed negligible to the overall HQ.

$$\mathbf{HQ} = \frac{\mathbf{EDI_{total}}}{\mathbf{TDI}} \qquad \textbf{Equation 32}$$

$$= \frac{2.4x10^{-5}\ mg/kg\ d}{5.0x10^{-3}\ mg/kg\ d} = 4.8\ x\ 10^{-3}$$

<u>Carcinogenic risk to an adult hiker not including food ingestion</u>

Soil Ingestion

$$\mathbf{LADD_{soil}} = \frac{\mathbf{EPC\ x\ IR_s\ x\ RAF_{oral}\ x\ ET_1\ x\ EF\ x\ CF_1 x\ ED}}{\mathbf{BW\ x\ AT}} \qquad \textbf{Equation 33}$$

$$= \frac{(62\,\frac{mg}{kg})(0.02g/d)(1)(5\,\frac{d}{7d})(1\,\frac{wk}{52wk})(1E-03\,\frac{kg}{g})(60yrs)}{70.7\ kg\ x\ 60\ yrs}$$

$$= 2.4\ x\ 10^{-7}mg/kg\ d$$

Dermal contact with soil

$$\mathbf{LADD_{dermal}} = \frac{\mathbf{(EPC\ x\ SA_h\ xSAF_h) + (EPC\ x\ SA_o\ x\ SAF_o)\ x\ RAF_{derm}\ x\ ET_1\ x\ EF\ x\ CF_1\ x\ ED}}{\mathbf{BW\ x\ AT}} \qquad \textbf{Equation 34}$$

$$= \frac{\left(62\,\frac{mg}{kg}\ x\ 890cm^2\ x1.0E-4\,\frac{g}{cm^2 d}\right) + \left(62\,\frac{mg}{kg}\ x\ 8220cm^2\ x\ 1.0E-5\,\frac{g}{cm^2 d}\right)\ x\ 0.03\ x\ (5\,\frac{d}{7d})(1\,\frac{wk}{52wk})(1E-03\,\frac{kg}{g})(60yrs)}{70.7kg}$$

$$= 6.2\ x\ 10^{-8} mg/kg\ d$$

Inhalation of Soil Particles

$$\mathbf{LADD_{inhalation}} = \frac{\mathbf{EPC\ x\ P_A\ x\ IR_A\ x\ RAF_{inh}\ x\ ET_1\ x\ ET_2\ x\ EF\ x\ ED}}{\mathbf{BW\ x\ AT}} \qquad \textbf{Equation 35}$$

$$= \frac{62\,\frac{mg}{kg}\ x\ 7.6x10^{-10} kg/m^3\ x\ 15.8\,\frac{m^3}{d}\ x\ 1\ x\ (5\,\frac{d}{7d})(6\,\frac{h}{24h})(1\,\frac{wk}{52wk})(60yrs)}{70.7kg\ x\ 60yrs}$$

$$= 3.6\ x\ 10^{-11} mg/kg\ d$$

Incremental Lifetime Cancer Risk

$LADD_{oral/dermal} = LADD_{soil\ ingestion} + LADD_{dermal\ contact}$

$$\mathbf{ILCR_{oral/dermal}} = \mathbf{LADD\ x\ CSF} \qquad \textbf{Equation 36}$$

$$= \left(3.34x10^{-7}\,\frac{mg}{kg}\,d\right)\left(1.8\,\frac{mg}{kg}\,d\right) = 5.5x10^{-7}$$

$$\mathbf{ILCR_{inhalation}} = \mathbf{LADD\ x\ CSF} \qquad \textbf{Equation 37}$$

$$= (3.6x\ 10^{-11} mg/kg\ d)(28\ mg/kg\ d)\ = 1.0x10^{-9}$$