# SOIL STERILANTS PROGRAM:
## KNOWLEDGE SYNTHESIS, RECOMMENDED PRACTICES AND GAPS

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## EXECUTIVE SUMMARY

Soil sterilants were commonly used from the 1960s to late 1990s to control weeds on rangelands, pipeline right of ways, oil and gas wells, railways, sawmills, pulp mills, and other industrial sites across Alberta. Sterilants are typically non-selective, residual, and persistent; they control all plants they contact and because they persist in soil, vegetation growth on sterilant-impacted sites is often inhibited. Sterilants tend to be highly mobile, which can result in off-site contamination via leaching, surface runoff, and wind. Two of the most used soil sterilants in Alberta were bromacil and tebuthiuron.

This report provides lessons learned and a summary of the remaining knowledge gaps derived from the research projects undertaken through the 5-year Soil Sterilants Program. Recommendations arising from the Program include:

**Improving sterilant identification and sampling**

- To reduce overall site management costs, emphasize quality environmental sites assessments (ESAs) to inform conceptual site models (CSMs). This is required for both risk-based and remediation management approaches.
  - Leverage guidance and support tools to identify sites and areas on a site most likely to be impacted by sterilants. Assume sterilants could be present if site was operational prior to 2000, particularly in agricultural regions of Alberta.
  - Leverage best practices described herein and associated SSP documents to inform CSM through Phase 1 and 2 ESA.
  - Do not rely on vegetation assessments as indicators of sterilant presence/absence.
- Install groundwater monitoring wells in initial Phase 2 ESA; data is required for CSM's and in Tier 2 Risk Assessment approaches.
- Develop strong QA/QC program.
- Collect soil and water samples in a manner that reduces potential cross-contamination.
  - Focus on how and what to sample to manage costs rather than application of field screening technologies.

**Improving detection and delineation of soil sterilants in soil and groundwater**

- Phyto-accessible (soluble) analytical method may provide useful data and "line of evidence" when applying a Tier 2 risk assessment approach and the Freshwater Aquatic Life (FAL) pathway can be eliminated OR if immobilization technologies are being (or have been) applied as a management tool.
  - Demonstrate the difference between total (non-soluble and soluble) and phyto-accessible (soluble) concentrations to develop a site-specific guideline to accompany Phase 2 data.
- Use accelerated solvent extraction (ASE) for soil samples and the solid-phase extraction method with an Autotrace 280 SPE for water samples. Analyze the extractant by LC-MS/MS or LC-Orbitrap-MS when low-level precision and accuracy are essential to project success.

**Improving risk assessment and management**

- Compare Phase 1 and 2 ESA and CSM to Tier 1 Guidelines as a first step to determine management options.
  - Always plan to assess groundwater when bromacil or tebuthiuron are present; install groundwater monitoring wells during the initial Phase 2 ESA in areas representative of "worst-case" scenario.
- Exclude pathways where applicable and determine if additional site-specific non-chemical-specific data (Db, foc, porosity, etc.) or chemical-specific parameters (half-life, Koc) would be beneficial for calculation of modified Guidelines through a Tier 2 approach.
  - Exclude FAL pathway if no surface water bodies are present within 300 m by (1) assessing the groundwater and monitoring sterilant plume characteristics; and (2) applying a conservative degradation half-life justified through literature or site-specific data.
  - Exclude Irrigation Water pathway if outside agricultural regions.
- Consider where the site is located and if agronomic or native species are intended for reclamation.
- To reduce risk to receptors, if equivalent land capability requires native grass species for reclamation consider using the alternate soil quality guidelines for Tier 1 ecological direct contact surface soil quality guidelines for fine-grained soil in non-commercial and non-industrial land uses.

**Improving remediation** (unless otherwise specified, the recommendations apply to both bromacil and tebuthiuron)

*Sterilants within surface soil (≤ 0.5 metres below ground surface (mbgs))*

- Conduct bench-scale tests with impacted soil to assess treatment application rates based on soil properties and Phase 2 ESA data for sterilant concentrations.
- Destructive and immobilization technologies must be applied in slurry form to optimize in-situ soil contact (recommended moisture content – 80% of soil water holding capacity).
- Apply immobilization technologies (i.e., Activated Carbon) in-situ.
- For destructive remediation technologies excavate impacted soil for treatment in a constructed treatment cell (on- or off-site).
  - Construct treatment cell to enable impacted soil depth within the cell to be ≥0.6 m.
- Bromacil: In-situ Chemical Reduction (ISCR) technology DARAMEND®
  - Monitor soil moisture during treatment to maintain moisture conditions and reducing soil environment.
  - Activated Carbon
- Tebuthiuron:
  - In-situ Chemical Oxidation (ISCO) $H_2O_2$ with catalyst and surfactant (requires further investigation).
  - Activated Carbon

*Sterilants at depths greater >0.5 mbgs in unsaturated soil*

- Excavate un-impacted soil to expose impacted zone and store on-site for reclamation.
- Excavate impacted soil and treat in a constructed treatment cell (on- or off-site) in the same manner as described above.

*Saturated fine-grained till soils and groundwater impacted by sterilants*

- Ex-situ – technologies and recommended practices described above apply.

*Groundwater impacted by sterilants*

- Applicable technologies for groundwater treatment described in Levy et al. (2021).

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## GLOSSARY

**Black Carbon**

Carbon-rich material derived from incomplete combustion of vegetation and fossil fuels, as well as mineral weathering. Biochar and activated carbon are forms of black carbon.

**Closure (Regulatory)**

The written approval and acceptance by a regulatory authority of remediation work at or offsite of a property in connection with a release.

**Community of Practice**

A collection of individuals involved in various aspects of the management of sterilant impacted sites, including practitioners, industry representatives, researchers, and regulators.

**Phyto-accessible**

Amount of a contaminant that is available to affect vegetation (i.e., is soluble and not bound to soil particles).

**Risk Assessment**

In the context of the Soil Sterilants Program, risk assessment involves identifying appropriate risk model(s) and model parameters to develop screening guidelines for bromacil and tebuthiuron deemed to be protective of relevant pathways based on the contaminants' real-world fate and mobility in the subsurface under Alberta field conditions (Litalien et al., 2020).

**Risk Management**

The identification of risk and the application of control measures, such as remediation and exposure controls, to reduce or eliminate risks (*Alberta Risk Management Plan Guide*; AEP, 2017).

**Risk Management Plan**

A plan employing the use of exposure control to manage risks posed by one or more contaminants of potential concern within one or more areas of potential concern.

**Tier 1 Guidelines**

Alberta Environment and Parks, 2019[1]. Alberta Tier 1 Soil and Groundwater Remediation Guidelines. Alberta Environment and Parks, Land Policy Branch, Policy and Planning Division. AEP, Land Policy, 2019, No. 1. 198 pp. https://open.alberta.ca/dataset/842becf6-dc0c-4cc7-8b29-e3f383133ddc/resource/a5cd84a6-5675-4e5b-94b8-0a36887c588b/download/albertatier1guidelines-jan10-2019.pdf

**Tier 2 Guidelines**

Alberta Environment and Parks, 2019[1]. Alberta Tier 2 Soil and Groundwater Remediation Guidelines. Alberta Environment and Parks, Land Policy Branch, Policy and Planning Division. AEP, Land Policy, 2019, No. 2. 150 pp. https://open.alberta.ca/dataset/aa212afe-2916-4be9-8094-42708c950313/resource/157bf66c-370e-4e19-854a-3206991cc3d2/download/albertatier2guidelines-jan10-2019.pdf

## ACRONYMS

| | |
|---|---|
| AC | Activated Carbon |
| APEC | Area of Potential Environmental Concern |
| ASE | Accelerated Solvent Extraction |
| bgs | Below Ground Surface |

[1] Most of the SSP reports referred to the 2019 Alberta Tier 1 Guidelines and Alberta Tier 2 Guidelines for bromacil and tebuthiuron guideline values. These guidelines were updated in 2022 (https://open.alberta.ca/publications/1926-6243), however none of the bromacil or tebuthiuron guideline values changed.

| | |
|---|---|
| CSM | Conceptual Site Model |
| DSC | Direct Soil Contact |
| EPA | Alberta Environment and Protected Areas |
| ESA | Environmental Site Assessment |
| ELISA | Enzyme-linked Immunosorbent Assays |
| FAL | Freshwater Aquatic Life |
| foc | Fraction of Organic Carbon |
| GC/TID | Gas Chromatography / Thermionic Ionization Detector |
| GC/PID | Portable Gas Chromatography / Photoionization Detector |
| GWQG | Groundwater Quality Guidelines |
| HPLC-MS | High-performance Liquid Chromatography Coupled to Mass Spectrometry |
| ICp | Inhibition Concentration |
| ISCO | In-situ Chemical Oxidation |
| ISCR | In-situ Chemical Reduction |
| IW | Irrigation Water |
| Kd | Distribution Coefficient |
| Koc | Organic Carbon Normalized Adsorption Coefficient |
| LC-MS | Liquid Chromatography Coupled to Mass Spectrometry |
| LC-MS/MS | Liquid Chromatography Coupled to Tandem Mass Spectrometry |
| LIBS | Laser-induced Breakdown Spectroscopy |
| mbgs | Metres Below Ground Surface |
| MDL | Minimum Detection Limit / Method Detection Limit |
| NAPL | Non-aqueous Phase Liquid |
| NIRS | Near Infrared Reflectance Spectroscopy |
| OIP | Optical Image Profiler |
| OM | Organic Matter |
| ORP | Oxidation Reduction Potential |
| PID | Photoionization Detector |
| PRB | Permeable Reactive Barrier |
| ssDNA MRE | Single-stranded DNA Molecular Recognition Element |
| SOP | Standard Operating Procedure |
| SPE | Solid-phase Extraction |
| SPLP | Synthetic Precipitation Leaching Procedure |

| | |
|---|---|
| SQG | Soil Quality Guidelines |
| SSP | Soil Sterilants Program |
| TOC | Total Organic Carbon |
| US EPA | United States Environmental Protection Agency |
| UV | Ultraviolet |
| v/v | Volume to Volume |
| XRF | X-ray Fluorescence |
| ZVI | Zero Valent Iron |

# 1.0 INTRODUCTION

Soil sterilants were commonly used from the 1960s to late 1990s for non-selective vegetation control on industrial sites in Alberta. Sterilants are unique contaminants that pose challenges for traditional assessment and delineation, remediation, and risk assessment and management. In addition, common soil types and hydrogeology in Alberta contribute to challenges in the management of soil sterilants. Bromacil and tebuthiuron were identified as the primary sterilants of concern in Alberta based on a literature review (Drozdowski et al., 2018a), and stakeholder consultation (Drozdowski et al., 2018b). Common characteristics of these two sterilants are provided in Appendix A. Many impacted industrial sites are either starting to be decommissioned or stalled at the remediation phase resulting in delayed reclamation and certification. Soils treated with sterilants can become a source of contamination to adjacent land and waterbodies through leaching, surface runoff, and wind dispersion.

The Soil Sterilants Program (SSP), funded by government and industry, was established to develop proven technical and cost-effective strategies and best management practices for management of sites impacted by residual soil sterilants, with the goal of achieving regulatory site closure or acceptable risk management for site owners.

This report provides learnings, recommended practices and a summary of the remaining knowledge gaps derived from the research projects undertaken through the 5-year Soil Sterilants Program in the areas of: (1) Identification and Delineation, (2) Risk Assessment and Management, and (3) Remediation (Figure 1). A report compiling the SSP research reports has been prepared (Powter and Drozdowski, 2025).

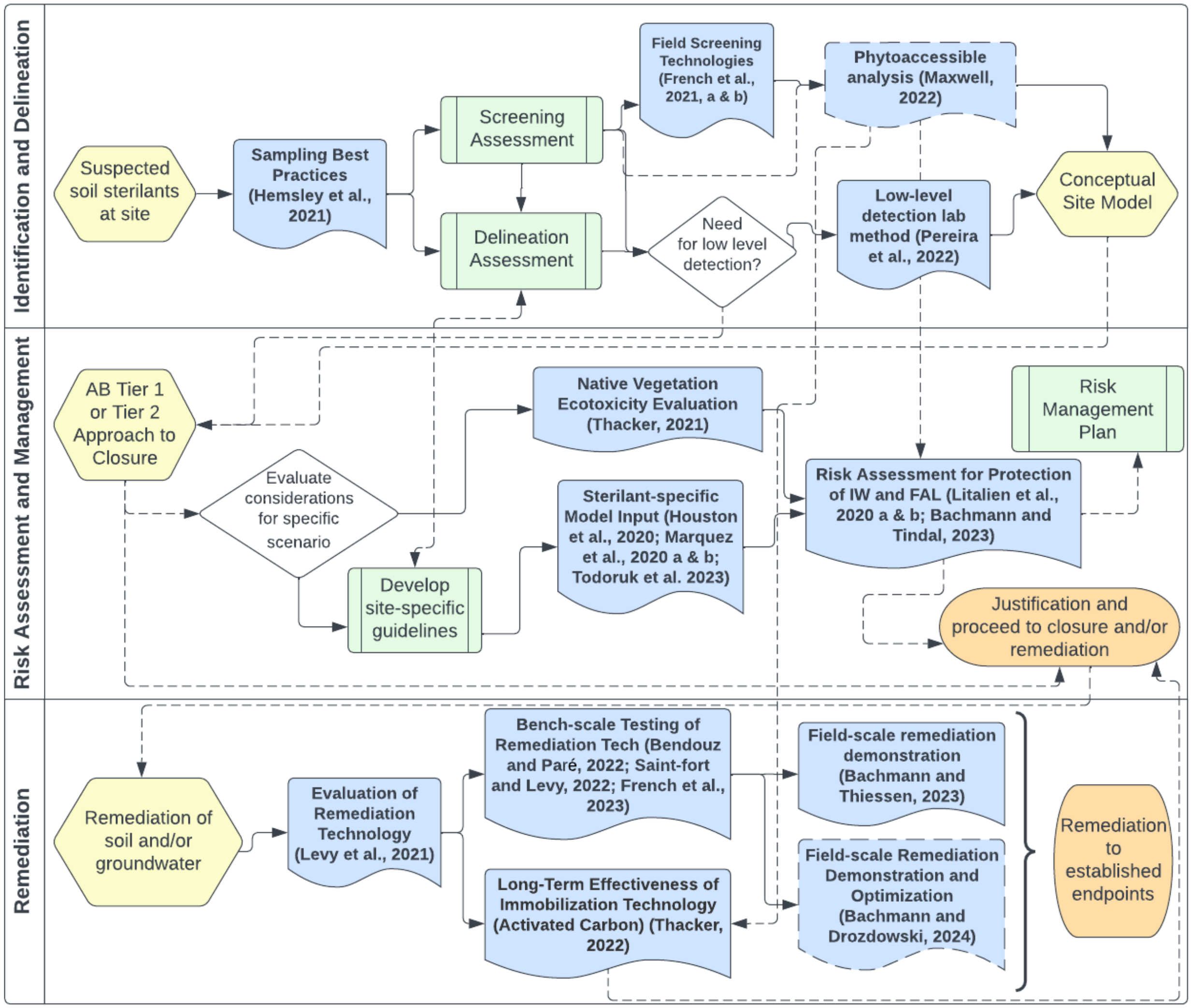



Figure 1. Research projects and interdependencies of projects undertaken through the Soil Sterilants Program in the areas of: (1) Identification and Delineation, (2) Risk Assessment and Management, and (3) Remediation.
Note – blue shapes indicate projects and references generated from the SSP.

## 1.1 Applicable Regulatory Considerations

Alberta's environmental regulatory framework is outlined within the *Environmental Protection and Enhancement Act* (EPEA; Government of Alberta, 2000) and associated Regulations. All findings from the SSP are intended to be used in conjunction with this framework. The management of contaminated sites is guided through the *Contaminated Sites Policy Framework* (EPA, 2023) with support from the *Alberta Environmental Site Assessment Standard* (AEP, 2016a), *Alberta Tier 1 Soil and Groundwater Remediation Guidelines* (Tier 1 Guidelines) (AEP, 2022a), *Alberta Tier 2 Soil and Groundwater Remediation Guidelines* (Tier 2 Guidelines) (AEP, 2022b), *Alberta Risk Management Plan Guide* (AEP, 2017) and the *Alberta Exposure Control Guide* (AEP, 2016b). The Tier 1 Guideline values for bromacil and tebuthiuron are very low and in some cases are less than the current laboratory detection limits (Table 1 and Table 2).

Table 1. Alberta Tier 1 soil guidelines for bromacil and tebuthiuron (agricultural land use).

| **Soil Sterilant** | **Alberta Tier 1 Guidelines (Agriculture Land Use)[1]** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Soil (Coarse-grained; mg/kg)** | | | | | | **Soil (Fine-grained; mg/kg)** | | | | | |
| | **Human** | | **Ecological** | | | | **Human** | | **Ecological** | | | |
| | **Direct Soil Contact** | **Domestic Use Aquifer** | **Direct Soil Contact** | **Freshwater Aquatic Life** | **Irrigation Water** | **Livestock Water** | **Direct Soil Contact** | **Domestic Use Aquifer** | **Direct Soil Contact** | **Freshwater Aquatic Life** | **Irrigation Water** | **Livestock Water** |
| Bromacil | 2,000 | 7.0 | 0.2 | **0.009** | BDL | 2.0 | 2,000 | 10 | 0.12 | **0.009** | BDL | 2.0 |
| Tebuthiuron | 1,600 | 2.5 | **0.046** | BDL | BDL | 0.12 | 1,600 | 3.7 | **0.046** | BDL | BDL | 0.11 |

[1] 2022 Alberta Tier 1 soil remediation guideline; BDL – below detection limit; groundwater assessment and comparison to groundwater remediation guidelines necessary; **Bold** – lowest applicable guideline.

Table 2. Alberta Tier 1 groundwater guidelines for bromacil and tebuthiuron (agricultural land use).

| **Soil Sterilant** | **Alberta Tier 1 Guidelines (Agriculture Land Use)[1]** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Groundwater (Coarse-grained; mg/L)** | | | | | | **Groundwater (Fine-grained; mg/L)** | | | | | |
| | **Human** | | **Ecological** | | | | **Human** | | **Ecological** | | | |
| | **Potable** | **Vapour Inhalation** | **Direct Soil Contact** | **Freshwater Aquatic Life** | **Irrigation Water** | **Livestock Water** | **Potable** | **Vapour Inhalation** | **Direct Soil Contact** | **Freshwater Aquatic Life** | **Irrigation Water** | **Livestock Water** |
| Bromacil | 0.95 | - | 0.44 | 0.005 | **0.0002** | 1.1 | 0.95 | - | 0.30 | 0.005 | **0.0002** | 1.1 |
| Tebuthiuron | 0.66 | - | 0.20 | 0.0016 | **0.00043** | 0.13 | 0.66 | - | 0.25 | 0.0016 | **0.00043** | 0.13 |

[1] 2022 Alberta Tier 1 groundwater remediation guideline; BDL – below detection limit; groundwater assessment and comparison to groundwater remediation guidelines necessary; **Bold** – lowest applicable guideline.

## 1.2 Alberta Context – Bromacil- and Tebuthiuron-impacted Sites

To enable a better understanding of sterilant presence, distribution and behaviour in field conditions in Alberta, interviews and a practitioner/industry survey of sites impacted by bromacil and tebuthiuron were conducted. The information was used to inform research priorities, experimental designs and ultimately to support sampling, risk management and remediation best practices.

Information on the depth of known contamination, vertical separation, groundwater contamination and range of concentrations in surface soil (≤1 metre below ground surface [mbgs]) and subsurface soils (>1 mbgs), both in fine- and coarse-textured soils was collated by reviewing data from 51 sites currently or historically impacted by bromacil and/or tebuthiuron across Alberta (Table 3) (Houston et al., 2020; Todoruk et al., 2023). Earlier literature and consultation indicated there were thousands of sterilant impacted sites across Alberta (Drozdowski et al., 2018a, b) suggesting data from 51 sites was a reasonable sample size to generate data from.

Sixteen of the 51 sites were identified as having coarse-grained soils while the remainder were fine-grained. Overall, bromacil and tebuthiuron concentrations were greater at depths greater than 1 mbgs. All sites with tebuthiuron also had bromacil as a co-contaminant; this complicates the risk management and remedial options since the two sterilants have distinct characteristics and properties and respond differently to treatment methods. Bromacil was absent from groundwater at sites with both coarse-grained (6 sites) and fine-grained (10 sites) soils, a range of hydraulic conductivities ($10^{-6}$ to $10^{-9}$ m/s), and variable depths to groundwater (0.96 to 11 mbgs). Co-contaminants at sites where groundwater was unimpacted by sterilants were generally limited to chloride and/or metals or were not present. Conversely, organic contaminants were more prevalent at the sites where groundwater was impacted by sterilants. Collectively, these data suggest that the fate and transport of sterilants in the environment are complex processes and support the idea that biodegradation is an important consideration at sterilant impacted sites in Alberta.

Table 3. Summary of bromacil and tebuthiuron impacts within coarse- and fine-textured soils.

| Description | Bromacil | Tebuthiuron |
|---|---|---|
| Depth of known impacts | 0 mbgs to 6 mbgs | 0.15 mbgs to 4.5 mbgs |
| Surface soil (≤1 mbgs) concentration range | 0.0085 mg/kg to 2.4 mg/kg | 0.000146 mg/kg to 0.0208 mg/kg |
| Subsurface soil (>1 mbgs) concentration range | 0.19 mg/kg to 3.0 mg/kg | 0.48 mg/kg to 1.81 mg/kg |
| Number of sites impacted (Groundwater impacted) | 46 (27 sites) | 10 (co-located with bromacil) (3 of 27 sites) |
| Vertical separation between impacted soil and measured groundwater depth – 0 m (Groundwater impacted) | 18 sites (14 of 18 sites) | 6 sites (2 of 6 sites) |
| Vertical separation between impacted soil and measured groundwater depth – 1 m to 5 m (Groundwater impacted) | 8 sites (3 of 8 sites) | 1 site (0 of 1 site) |
| Vertical separation between impacted soil and measured groundwater depth – >5 m to 10 m (Groundwater impacted) | 4 sites (1 of 3 sites) | None |

Table adapted from Hemsley et al. (2021) with information from Houston et al. (2020) and Gainer and Todoruk (2023).

Table 4 summarizes sterilant distribution at Alberta sites (Drozdowski et al., 2018; Gainer and Todoruk, 2023; Houston et al. 2020; Levy et al., 2021).

Table 4. Summary information related to sterilant-impacted sites in Alberta.

| Summary Information | |
|---|---|
| • Bromacil is the more prevalent sterilant.<br>• Co-contaminants are found at most sterilant-impacted sites.<br>• Sites often have both fine- and coarse-grained soils, with the majority dominated by fine-grained.<br>• Vegetation impacts cannot always be used to identify sterilant impacts, as sites may be graveled.<br>• Small soil 'hot spots' are often found across a site. | • Majority of sites have sterilant impacts below surface and into shallow groundwater.<br>• Sterilant delineation is challenging and only achieved approximately 50% of the time.<br>• Inactive and dormant sites may not be regularly monitored.<br>• Surface soil can meet guidelines but sterilants at the same sites can be found deeper in the profile. |

### 1.3 Management Practices and Challenges Related to Sterilant-impacted Sites in Alberta

Literature review and consultation yielded the following information on historical and current activities related to management of sterilant-impacted sites in Alberta (Drozdowski et al., 2018a, b; Levy et al., 2021):

- Risk assessment (i.e., Tier 2 approaches including site specific risk assessment (SSRA)) and risk management (i.e., exposure control, administrative or engineering controls) were most often employed in sterilant management, followed by remedial excavation and disposal where risk could not be managed otherwise.
- Several remediation technologies have been trialed and used with varying degrees of success for management of sterilant-impacted sites, including, but not limited to, thermal desorption, activated carbon, permeable reactive barrier and/or pump and treat with chemical oxidants, and photocatalysis. A detailed evaluation of ex-situ and in-situ soil and water remediation technologies was completed by Levy et al. (2021) and technologies were categorized by proven, impractical, and potential application for management of sterilant-impacted sites.

High priority risk management and remediation challenges were identified through the literature review and consultation process and were used to identify research priorities and technology selection to inform best practices for sterilant impacted sites (Table 5; Levy et al., 2021). A key consideration for all scenarios identified is whether the primary goal is to address high concentrations to reduce risk, or lower concentrations to meet remediation endpoints. Technologies and management strategies should be selected according to the end goal. Given the heterogeneous distribution of sterilants on sites and unique conditions at most sites, a variety of approaches may be required at each site.

Table 5. High priority risk management and/or remediation challenges and technology considerations.

| **High Priority Risk Management and/or Remediation Challenges** | **Considerations for Technology Application** |
|---|---|
| Sterilants within surface soil (≤ 0.5 mbgs) | • Accessible via in-situ technologies.<br>• Validation of remediation endpoints required to assess applicability of Tier 1 or Tier 2 Guidelines. |
| Sterilants at depths > 0.5 mbgs in unsaturated soil | • Inaccessible to treatment at surface.<br>• Ideally the technologies to address deeper sterilants would function in-situ to minimize excavation of overlying soil. |
| Soil treatment requirements where sterilant destruction is required, and immobilization is not considered an acceptable option | • Technologies for this application could be in-situ *or* ex-situ. |
| Saturated fine-grained till soils and groundwater impacted by sterilants | • Where sterilants are widely dispersed, in-situ technologies and/or combinations thereof to avoid remedial excavation and disposal of >5,000 to 10,000 tonnes of soil and underlying groundwater would be beneficial. |
| Groundwater impacted by sterilants | • Technologies that can prevent off-site migration.<br>• Technologies that can treat impacts in-situ or ex-situ. |

# 2.0 IDENTIFICATION AND DELINEATION

## 2.1 Problem Statement

Sterilant impacts are often widespread and difficult to detect due to the amount of time they have had to migrate therefore practitioners are uncertain about when and where to screen for soil sterilants, leading to unnecessary intrusive sampling following Phase I environmental sites assessments (ESA), excessive and/or uncertain analysis due to cross contamination (and associated cost), and identification of sterilants late in the assessment process that cause reclamation delays.

Additionally, analytical methods currently used in Alberta to characterize sterilants found in soil and/or water have variable detection limits, sometimes higher than guideline levels, and only provide total (soluble and non-soluble), rather than phyto-accessible (soluble), concentrations.

The SSP addressed these challenges through assessment of sampling practices and analytical technologies and methods (Figure 2).

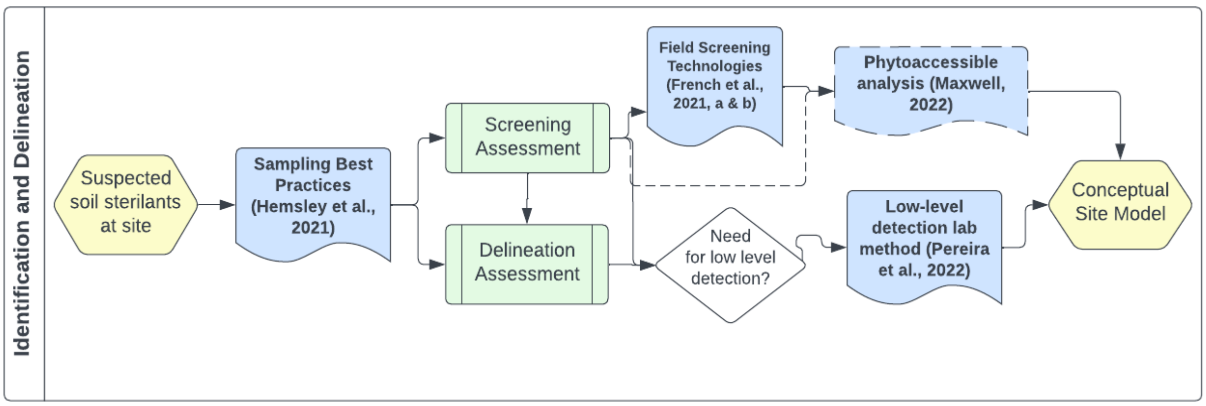



Figure 2. Identification and delineation projects.

## 2.2 Sterilant Identification and Sampling Best Management Practices

A sampling Best Management Practices report was prepared for practitioners involved in environmental site assessment or remediation and reclamation activities at sterilant-impacted sites (Hemsley et al., 2021). The document provides guidance on regulatory considerations, site evaluations, soil and groundwater characterization (e.g., soil sampling, groundwater sampling), and data evaluation and interpretation specific to bromacil and tebuthiuron. To ensure sterilants are effectively identified and delineated, the following should be considered when developing a sampling program:

- Site historical information and characteristics (e.g., age of site, likelihood of sterilant application, low-lying areas, slopes, soil classification, hydraulic characteristics).
- Objectives of the site investigation. Is it an initial assessment? Or a supplemental (detailed) assessment? Or for delineation?
- The fate and transport (volatilization, absorption/desorption, mobility/leaching, soil pH and salinity) of the sterilants.
- Situations with high potential for cross contamination when sampling.

- The spatial variability of both soils and sterilants as high concentrations of sterilants may be found at the surface or at depth within ‘hot spots’ but they may diminish to below laboratory detection limits in a short distance.

The high potential for cross-contamination when sampling for sterilants requires special sampling techniques that address the low detection limits of bromacil and tebuthiuron analysis (Table 6). Specific considerations for identifying and delineating sterilants in Phase 1 and 2 ESAs are summarized in Figure 3.

Table 6. Sampling guidance for sterilant-impacted soil and groundwater.

| General Guidance | Soil | Groundwater |
|---|---|---|
| Take at least 1 field duplicate for every 10 samples and 1 trip blank per shipping container and 1 field equipment blank per day to confirm the presence or absence of cross-contamination during field activities, travel, or laboratory analysis for soils and groundwater. | Start sampling the areas where you expect the lowest sterilant levels and work progressively towards the areas with the highest expected sterilant levels. | Install groundwater monitoring wells to delineate suspected sources and impacts.<br><br>Change sampling equipment between well development, purging and sampling. |
| Collect and analyse decontaminated equipment rinsate to document the absence of cross-contamination. | Collect samples using a hollow stem auger with an 18” (45 cm) split barrel spoon with 6” (15 cm) x 2.5” (6 cm) stainless steel sleeves every 1.0 m down to a depth of 7.5 m or until bedrock. Collect at least 100 g for lab analysis. | Obtain at least two groundwater samples on different days from any monitoring well.<br><br>Establish discrete monitoring points within different water bearing lithological units to avoid mixing of groundwater during drilling and sampling. |
| Keep samples cool (around 4°C) and out of direct sunlight during transportation and storage. | Seal each soil-filled sleeve with Teflon™ tape and plastic caps and submit directly to the laboratory for analysis. | Use low flow purging and sampling for shallow depths. |
| Triple-rinse equipment using Liquinox and distilled water before each sample is taken. | Store soil samples in amber glass wide-mouth jars with Teflon™-lined lids. | Collect water samples in one-litre amber glass bottles and fill so there is no headspace. |

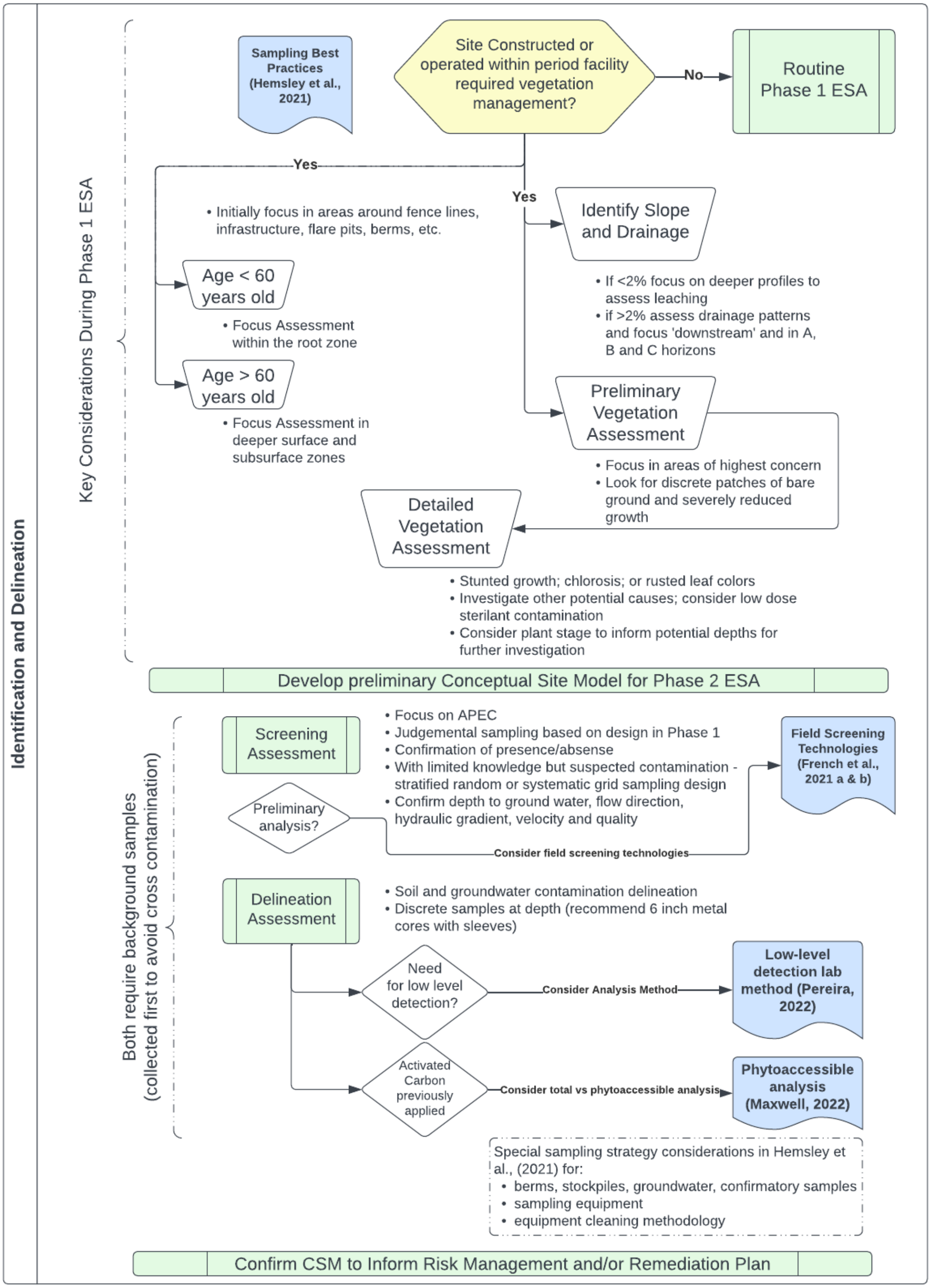



Figure 3. Considerations for identifying, assessing, and delineating sterilants. Information extracted from Hemsley et al. (2021); French et al. (2021a, b); Pereira et al. (2022); and Maxwell (2022).

## 2.3 Sterilant Detection and Analysis

### *2.3.1 Field Screening Technologies*

Preliminary technologies for screening sterilants in the field were investigated to minimize the costs and timelines associated with identification, quantification, and delineation of bromacil and/or tebuthiuron in soil and/or water at impacted sites. A literature review, preliminary testing, and interviews completed in relation to the potential application of existing field screening technologies concluded that only two of the technologies evaluated were suitable for further testing. Technologies were evaluated based on their ability to detect bromacil or tebuthiuron in spiked silica sand or spiked distilled water, and the following technologies were recommended for further investigation and/or optimization (French et al., 2021a, b):

- X-ray fluorescence (XRF): potentially for bromacil in soil samples; and
- Raman spectroscopy: potentially for bromacil and tebuthiuron in soil and water samples.

Upon further study and evaluation, the detection limits and/or portability of the equipment make the technologies unsuitable for field screening for soil sterilants without further technology development and advancement. In addition, two biosensor technologies were investigated (ssDNA MRE and ELISA), both of which were deemed unsuitable for field screening of bromacil or tebuthiuron (French et al., 2021b). However, immunochromatographic assays with nanomaterials have been developed for portable monitoring and could be considered for development in field screening for bromacil. Table 7 provides a summary and recommendations for field screening technologies for bromacil and tebuthiuron investigated in the SSP.

Table 7. Summary and recommendations for field screening technologies for bromacil and tebuthiuron investigated in SSP. From French et al. (2021 a, b).

| Technology/Analysis | Technology Summary | Preliminary Testing Results |
|---|---|---|
| Ultraviolet laser induced fluorescence (UVOST® or OIP®) | • Uses ultraviolet laser to excite molecules of the compound of interest to produce fluorescence.<br>• Usually used for non-aqueous phase liquids in a direct-push platform. Can be used in ex-situ samples.<br>• Typically used for high concentration NAPLs and not dissolved phase contaminants. | • UVOST detects bromacil-based Alligare 80 at 1,000 mg/L in water and tebuthiuron at 100 mg/L.<br>• Did not detect bromacil-based Hyvar XL.<br>• Detection limits too high for field screening and refinement to target minimum detection limit (MDL) unlikely. |
| Visible light laser induced fluorescence (TarGOST® or OIP-G®) | • Same technology as UVOST and optical image profiler (OIP) with a green visible wavelength.<br>• Does not identify dissolved-phase compounds. Detects high molecular weight like coal tar and heavy crudes. | • Not successful at detecting bromacil or tebuthiuron. |
| Near infrared reflectance spectroscopy (NIRS) | • Uses near IR reflectance spectrometry to detect compounds. Scatter and absorption are unique to certain molecules.<br>• Non-destructive, portable, and can detect as low as ppb with previous confirmed bromacil detection.<br>• High water content soils interfere with readings. Can theoretically directly test water samples. Tebuthiuron may be detectible by NIRS, but not confirmed. | • Not successful at detecting bromacil or tebuthiuron at low level concentrations. |
| X-ray fluorescence (XRF) | • Uses the scattering and absorption of x-ray light to determine the chemical properties of a sample.<br>• Non-selective and shows a spectrum of the relative amounts of components within a sample.<br>• Detects at the ppm range and is not capable of extremely low detection limits. Has been used to identify foliar applied herbicides but not for bromacil and tebuthiuron. | • XRF successful in detecting bromacil at 100 mg/kg and tebuthiuron at 1,000 mg/kg in spiked soil.<br>• Optimization for bromacil detection in soil initially recommended.<br>• Detection limit too high and refinement to target MDL unlikely for tebuthiuron. |

| Technology/Analysis | Technology Summary | Preliminary Testing Results |
|---|---|---|
| MISA Raman spectroscopy | • Uses laser light scattering on molecules. Can be set up in lab or field for non-destructive testing of soil or water.<br>• Has been used to measure bromacil degradation in soil. No information on using it to detect tebuthiuron. | • Successful in detecting bromacil at 100 mg/L in aqueous solutions with no extraction and 10 mg/L with chloroform extraction.<br>• Optimization may reach target MDL for this technology. |
| Laser-induced breakdown spectroscopy (LIBS) | • Uses high energy laser pulse to ionize and excite atoms in a sample that evaporates some of the sample in the production of plasma. The light from the plasma is analyzed to determine the chemical components of the sample.<br>• Appears that bromacil and tebuthiuron are in the range of identification of currently available LIBS instruments, but they have not been used specifically for these sterilants. | • Not successful at detecting bromacil or tebuthiuron. |
| Gas chromatography/ thermionic ionization detector (GC/TID) | • No easily field deployable instrument is available for this technology.<br>• There are field trucks fitted with these instruments, but they are specialized vehicles designed for GC investigations. | • No testing completed. |
| Portable gas chromatography/ photoionization detector (GC/PID) | • PIDs are suitable for volatile organic compounds.<br>• Bromacil and tebuthiuron are not volatile at ambient temperatures and PID instruments do not have bromacil or tebuthiuron as detectible compounds.<br>• GC has been used to determine bromacil and tebuthiuron in lab settings. There are no field-ready setups to detect these compounds. | • No testing completed. |
| Single-stranded DNA molecular recognition element (ssDNA MRE) | • ssDNA aptamer for bromacil not reliable. Selected aptamer does not bind to bromacil.<br>• Aptamer approach could be viable, though new aptamer selection experiments would be required. | • Not suitable for field screening. |
| Enzyme-linked immunosorbent assays (ELISA) | • Antibody test reliable and sensitive.<br>• The process requires multiple incubation and washing steps.<br>• Takes 4 hours in a typical assay. | • Not suitable for field screening.<br>• Immunochromatographic assays with nanomaterials have been developed for portable monitoring and should be considered for development in field screening for bromacil. |

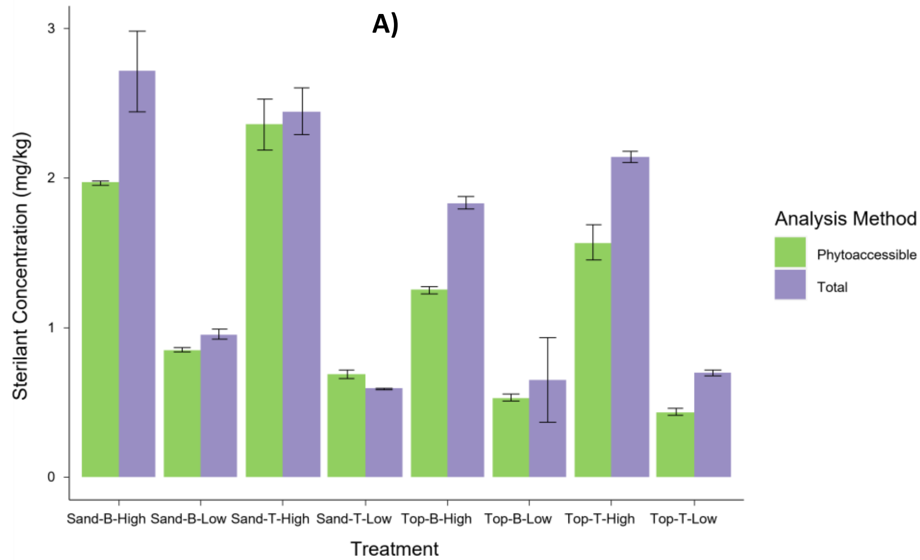
### *2.3.2 Phyto-accessible Sterilants Analytical Method*

Tier 1 Guidelines currently assume that the sterilants present in soil are always 100% accessible to plants under all conditions. However, sterilants adsorbed to the soil (organic matter, clay, or immobilization treatment technology) are not phyto-accessible, therefore using a phyto-accessible analytical method for analysing bromacil and tebuthiuron is more applicable as plants are the most sensitive receptor when considering the Direct Soil Contact (DSC) pathway (Stantec Consulting Ltd., 2008, 2012). Analyzing soil samples for total sterilant concentration precludes immobilization as a remedial method. Measuring phyto-accessible or soluble herbicide concentrations in soil rather than total concentrations can inform actual risk to susceptible receptors, confirming the validity of immobilization remediation technologies and resulting in less need for ex-situ soil treatment or landfilling.

Methods employed to assess total sterilant concentration use methanol as an extractant, which results in a measurement that does not differentiate between adsorbed and water-soluble fractions. A 0.01 M calcium chloride ($CaCl_2$) solution is often used to assess soluble (phyto-accessible) concentrations of nutrients and to conduct adsorption/desorption studies of metals and organics.

Maxwell (2022) used 0.01 M $CaCl_2$ as an extractant to estimate the phyto-accessible concentrations of bromacil and tebuthiuron in soil, demonstrating that phyto-accessible concentrations were approximately 50% ***less than*** total sterilant concentrations. The study also confirmed that soil organic matter is a significant naturally-occurring adsorbent of bromacil and tebuthiuron resulting in reduced phyto-accessibility. Adsorbed bromacil and tebuthiuron increased with increased organic matter but not with increased clay content. Thacker (2022) investigated use of the phyto-accessible method compared to total sterilant analysis in conjunction with sterilant immobilization experiments in topsoil and silica sand with and without amendment with activated carbon. The phyto-accessible sterilant fraction was lower than the initial, total sterilant concentration in soil, except for one treatment in unamended soils (Figure 4A). The phyto-accessible fraction in soils amended with activated carbon was much lower compared to the non-amended soil, indicating that the sorption of sterilants to activated carbon reduced phyto-accessibility (Figure 4B).

Site-specific conceptual models can be informed by the conclusions from Maxwell (2022) [and Thacker, 2022] to manage bromacil and tebuthiuron soil impacts in-situ with activated carbon.



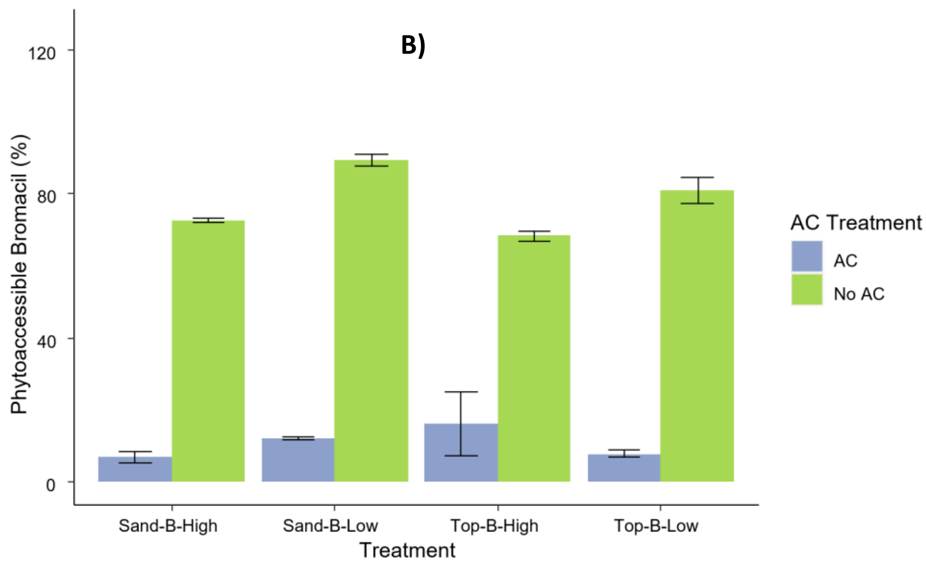




Figure 4. Total and phyto-accessible sterilant concentrations and the effect of activated carbon on phyto-accessible sterilant levels.
A) Sterilant concentration (mg/kg) in topsoil and silica sand, without activated carbon (AC) amendment, determined by either phyto-accessible or total sterilant analysis.
B) phyto-accessible bromacil (%) in topsoil and silica sand, either amended with activated carbon (AC), or non-amended. Bars represent means and error bars indicate the standard error.
Note that in treatment names, Sand = silica sand, Top = topsoil, B = bromacil,
T = tebuthiuron. High refers to the higher sterilant concentration (target 2.4 mg/kg), and Low refers to the lower sterilant concentration (target 0.8 mg/kg).
From Thacker (2022).

### *2.3.3 Low-level Laboratory Analytical Method*

Analytical methods related to total sterilant concentrations in Alberta commercial laboratories are mainly based on liquid chromatography with ultraviolet detection (LC-UV), liquid chromatography coupled to mass spectrometry (LC-MS), and gas chromatography coupled to mass spectrometry (GC-MS). Most of the academic research between 1984 and 2020 also used the same analytical techniques, however in later years methods moved from simple UV detection and low-resolution mass spectrometry to high-resolution mass spectrometry. Sample preparation has also moved from solvent extractions to solid-phase extraction (SPE) or accelerated solvent extraction (ASE) processes. However, despite advances in both analytical and extraction methods, detection limits in commercial laboratories are still very near Tier 1 Guidelines (AEP, 2022a) and results often vary between laboratories.

Development of test methods to increase the effectiveness and efficiency in laboratory analytical methodologies for detection of total bromacil and tebuthiuron focused on two components of the chemical measurement process: optimization of extraction approach and instrumentation (Pereira et al., 2022). New analytical methods for analysis of bromacil and tebuthiuron using reverse-phase liquid chromatography paired with either a linear ion trap-Orbitrap mass spectrometer or a triple quadrupole mass spectrometer were successfully developed and validated with detection limits between two and three orders of magnitude lower than available through commercial laboratories. Specific details associated with the revised, low level analysis methods can be found in Pereira et al. (2022). Table 8 provides a comparison of the methods and associated detection limits.

Table 8. Summary of laboratory extraction and detection methods for analysis of bromacil and tebuthiuron in soil and water.

| **Laboratory Method** | **Bromacil** | | **Tebuthiuron** | |
|---|---|---|---|---|
| | **Soil/Sediment** | **Water** | **Soil/Sediment** | **Water** |
| Commercial Laboratory Extraction Method | 99% methanol | Dichloromethane, methylene chloride** | 99% methanol | Dichloromethane, methylene chloride** |
| Commercial Laboratory Detection Method | High performance liquid chromatography with ultraviolet detection (HPLC-UV), high performance liquid chromatography coupled to mass spectrometry (HPLC-MS), gas chromatography coupled to mass spectrometry (GC-MS) | | | |
| Commercial Laboratory Detection Limit* | >5 µg/kg | ≥ 0.1 µg/L | ≥ 5 µg/kg | ≥ 0.1 µg/L |
| **Tier 1 Guideline** | **9 µg/kg** | **0.2 µg/L (IW)** | **46 µg/kg** | **0.43 µg/L (IW)** |
| Low Level Extraction Method*** | ASE | SPE | ASE | SPE |
| Low Level Detection Method | Reverse-phase liquid chromatography paired with either a triple quadrupole mass spectrometer (LC-MS/MS) or a linear ion trap-Orbitrap mass spectrometer (LC-Orbitrap-MS) | | | |
| LC/MS (LC-MS/MS) | 0.013 µg/kg | 0.0001 µg/L | 0.003 µg/kg | 0.000004 µg/L |
| LC-Orbitrap-MS | 0.032 µg/kg | 0.00006 µg/L | 0.006 µg/kg | 0.000004 µg/L |

* Varies based on detection method; ** Varies based on the laboratory; ***ASE = Accelerated Solvent Extraction; SPE = Solid-Phase Extraction

Use of low-level soil/sediment sample extraction (accelerated solvent extraction (ASE)) and water sample extraction (solid-phase extraction (SPE)) coupled with LC/MS or LC-Orbitrap were able to achieve detection limits between two and three orders of magnitude lower than available through commercial laboratories. However, the cost of the extraction and analysis is significantly higher due to the additional equipment required and may not be warranted. Detection limits for bromacil and tebuthiuron were improved by both the revised sample preparation and extraction methods and the analytical instruments used. Depending on the sterilant concentrations at a site relative to the laboratory method detection limit different analytical approaches could be applied (Table 9). A study to assess the benefits of the sample preparation and extraction methods with conventional analytical instruments to determine if better precision and accuracy could be achieved to assess impacts near Tier 1 limits more cost effectively is recommended.

Table 9. Applicable analytical methods based on required Method Detection Limit.

| Sterilant Impacts | Analytical Need | Method Available | Method Possible |
|---|---|---|---|
| Sterilant concentrations well above Tier 1 limits | Method with MDL* near Tier 1 limit (Same Order of Magnitude [OoM]) | Most commercial laboratory services | √ |
| Sterilant concentrations near Tier 1 limits (within same order of magnitude) | Method with MDL ~1 OoM less than Tier 1 limit<br>More refined precision and accuracy statements | Research required | ASE or SPE coupled with conventional analytical instruments (HPLC-UV, HPLC-MS, or GC-MS) |
| Sterilant concentrations below Tier 1 limits (greater than one order of magnitude) | Method with MDL as low as possible (maximum OoM less than Tier 1) | InnoTech Alberta (ASE or SPE coupled with LC-MS/MS or LC-Orbitrap-MS) | √ |

*Method detection limit

## 2.4 Knowledge Gaps and Recommended Practices

Remaining and/or new knowledge gaps associated with identification and delineation of soil sterilants that would support more effective management of sites impacted by soil sterilants include:

- Field Screening Technologies
    - Use of X-ray fluorescence (XRF) for detection of bromacil in soil samples in the field and Raman spectroscopy for bromacil and tebuthiuron in soil and water samples in the field would significantly reduce delineation costs and timelines for remediation and reclamation. Technologies are currently either too difficult or time consuming to use effectively in the field or not sensitive enough to inform meaningful decisions. Further research and development in low-level, portable detection technologies would be beneficial for more effective identification and delineation of sterilant impacted sites.
- Analytical Methods
    - To ensure acceptance of the phyto-accessible (soluble) detection method further investigation is required to
        - correlate phyto-accessible sterilant levels with vegetative survival and growth, and

        - test a broader range of soil clay (Maxwell (2022) used soil clay contents ranging from 16% to 18%) and organic contents.
    - The low-level analytical method investigated through the SSP indicated that lower detection levels could be accomplished using conventional analytical equipment if an alternative extraction method was utilized.  Further investigation is required for confirmation followed by an interlaboratory study and proficiency testing.

Table 10 provides a summary of recommended practices for effective identification, detection and delineation of bromacil and tebuthiuron in soil and groundwater.

Table 10. Recommended practices associated with effective identification and delineation of bromacil and tebuthiuron.

| Site Management Stage | Recommended Practices |
|---|---|
| Sterilant identification and sampling | • To reduce overall site management costs, emphasize quality environmental sites assessments (ESAs) to inform conceptual site models (CSMs). This is required for both risk-based and remediation management approaches.<br>o Leverage guidance and support tools to identify sites and areas on a site most likely to be impacted by sterilants. Assume sterilants could be present if site was operational prior to 2000, particularly in agricultural regions of Alberta.<br>o Leverage best practices described herein and associated SSP documents to inform CSM through Phase 1 and 2 ESA.<br>o Do not rely on vegetation assessments as indicators of sterilant presence/absence.<br>• Install groundwater monitoring wells in initial Phase 2 ESA; data is required for CSM's and in Tier 2 Risk Assessment approaches.<br>• Develop strong QA/QC program.<br>• Collect soil and water samples in a manner that reduces potential cross-contamination.<br>o Focus on how and what to sample to manage costs rather than application of field screening technologies. |
| Detection and delineation of soil sterilants in soil and groundwater | • Phyto-accessible (soluble) analytical method may provide useful data and "line of evidence" when applying a Tier 2 risk assessment approach and the Freshwater Aquatic Life (FAL) pathway can be eliminated OR if immobilization technologies are being (or have been) applied as a management tool.<br>o Demonstrate the difference between total (non-soluble and soluble) and phyto-accessible (soluble) concentrations to develop a site-specific guideline to accompany Phase 2 data.<br>• Use accelerated solvent extraction (ASE) for soil samples and the solid-phase extraction method with an Autotrace 280 SPE for water samples. Analyze the extractant by LC-MS/MS or LC-Orbitrap-MS when low-level precision and accuracy are essential to project success. |

# 3.0 RISK ASSESSMENT AND MANAGEMENT

## 3.1 Problem Statement

Under Alberta's framework for the management of contaminated sites (EPA, 2023) three options exist: Tier 1, Tier 2, and exposure control. Where Tier 1 takes a generalized approach, Tier 2 allows for the inclusion of site-specific conditions while providing the same level of protection to receptors as generic Tier 1 guidelines. Bromacil and tebuthiuron are mobile and persistent sterilants that are toxic to terrestrial and aquatic plants at low concentrations. These factors have contributed to very low Tier 1 guidelines for the irrigation water (IW) and freshwater aquatic life (FAL) pathways. EPA's risk assessment model considers partitioning of solutes, unsaturated transport, groundwater mixing, and lateral transport. With Tier 2 Guidelines, some site-specific factors can be included but are still limited which may result in overly conservative guidelines.

Specific challenges as they relate to application of these Guidelines to bromacil and tebuthiuron include:

- The values of the irrigation water (IW) and freshwater aquatic life (FAL) soil and groundwater guidelines calculated under the current Alberta Tier 1 framework (AEP, 2022a) are lower than the corresponding ecological direct contact guidelines and in some cases are below current analytical detection limits.
- The current Alberta Tier 1 guideline document does not include a value for degradation half-life for either bromacil or tebuthiuron. The lack of a degradation half-life is a major challenge to the overall management of these sterilants.
- Sterilant toxicity data for Alberta native plant species is incomplete or missing.

The SSP addressed these challenges through a thorough investigation of applicable risk models and input parameters applicable to soil sterilants (Figure 5).

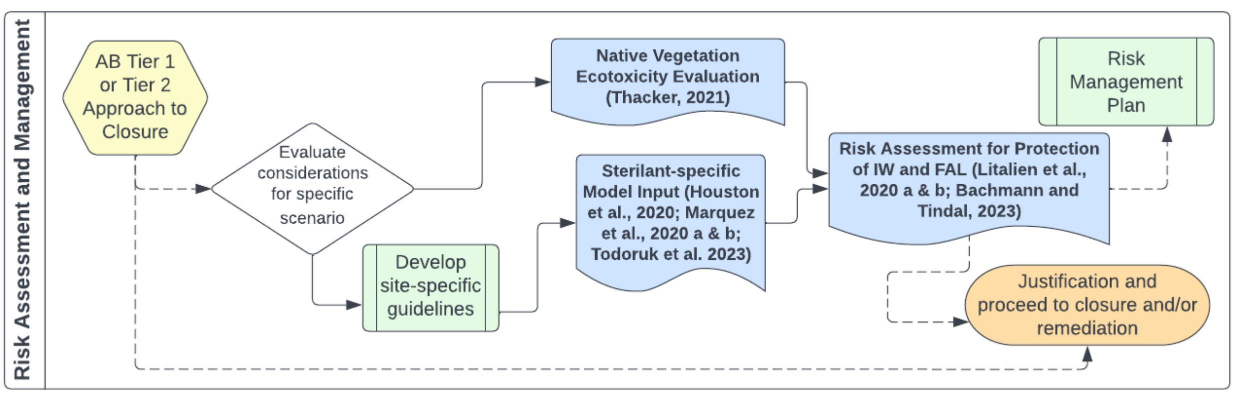



Figure 5. Risk assessment and management projects.

## 3.2 Risk Assessment Modelling

The Alberta Tier 1 soil screening guidelines for soil sterilants were developed using *A Protocol for the Derivation of Environmental and Human Health Soil Quality Guidelines* (CCME, 2006) as a starting point and adapted as necessary to reflect Alberta conditions and for developing groundwater screening guidelines (Litalien et al., 2020). Currently, the combination of the risk model used and assumptions within the risk model for the derivation of the Alberta Tier 1 screening guidelines for bromacil and tebuthiuron have resulted in guidelines which are often considered to be over-conservative in many cases.  The parameter values used in the risk models that calculate the Alberta Tier 1 Soil and Groundwater Remediation Guidelines fall into two main groups: (1) parameters relating to receptor exposure and properties of the site, referred to as “non-chemical-specific parameters”; and, (2) parameters that relate to the chemical properties, toxicity, or background exposure to chemicals, referred to as “chemical-specific parameters” (AEP, 2019).  The overall objective of analysis and experimentation in the SSP was to determine appropriate risk model(s) and model parameters to develop screening guidelines for bromacil and tebuthiuron deemed to be protective of the IW and FAL pathways and better reflect the contaminants “real-world” fate and mobility in the subsurface under Alberta field conditions.

Risk assessment input parameters related to contaminant fate, mobility, and degradation that more realistically reflect Alberta-specific field conditions, are protective of receptors at Alberta sites, and can be used to inform Tier 2 Guideline calculations for site closure are required.  Remedial endpoint (i.e., guideline) modification using the available Alberta Tier 2 risk assessment models (AEP, 2022a, b) to develop Tier 2 Soil and Groundwater Remediation Guidelines (AEP, 2022b) can be an effective and relatively inexpensive approach to site management when sterilants are present.  The intent of Tier 2 Guidelines is to provide a level of protection equivalent to Tier 1 Guidelines.  However, as the model input parameters available within the Tier 2 Guidelines are also conservative, they may not reflect actual field conditions at specific sites or Alberta sites in general (Litalien et al., 2020a; Marquez et al., 2019).

The Tier 1 guidelines use the Domenico and Robbins groundwater transportation model (Domenico model; Domenico, 1987; Domenico and Robbins, 1985) which uses physico-chemical properties, soil properties, geometric parameters, and flow parameters to evaluate transport of chemical contaminants from a source in soils to groundwater to a nearby surface water body.  The Tier 1 and 2 model for calculating soil guidelines protective of the IW and FAL pathways is comprised of four dilution factors (DF) including:

| | |
|---|---|
| DF1 | • Represents partitioning of the contaminant between soil, pore water, and soil vapour.<br>• Considers how a contaminant may sorb to soil organic matter and mineral soil particles. |
| DF2 | • Represents the ratio of the concentration of the contaminant in porewater at the source to that of the porewater just above groundwater.<br>• Includes dilution due to biodegradation and dispersion as the contaminant moves down through the soil profile.<br>• Equal to 1 in Tier 1 (assumed source of contamination extends to shallow groundwater). |
| DF3 | • Represents the ratio of the concentration of the contaminant in porewater just above groundwater to the concentration in groundwater.<br>• Addresses mixing between vadose zone pore water and groundwater. |
| DF4 | • Represents the dilution that occurs due to dispersion and biodegradation as groundwater travels downgradient from the source to a receptor.<br>• Calculated based on assumption that distance between source and FAL receptor is 10 m in Tier 1. |

For Tier 2 guideline adjustments, some site-specific factors can be included but are limited, which may result in overly conservative guidelines for application to Alberta sites.  Additional research and analysis were required to inform Tier 2 Guideline modifications and calculations that are acceptable to regulators and more realistically reflect Alberta-specific field conditions and are protective of receptors:

- Undertake sensitivity analysis to determine key model input parameters influencing soil and groundwater Guidelines for bromacil and tebuthiuron.

- Conduct laboratory experiments using Alberta field soils to measure half-life under varying conditions and estimate soil organic-carbon partition coefficients (Koc) for bromacil and tebuthiuron.
- Evaluate alternative models that could adjust IW and FAL pathways for bromacil and tebuthiuron.
- Review literature to identify degradation mechanisms and associated metabolites for bromacil and tebuthiuron to inform analytical methods and risk evaluation.

This information is also useful and applicable for Tier 2 Site Specific Risk Assessment data collection.

### *3.2.1 Model Sensitivity Analysis*

Domenico model sensitivity analysis included several model input parameters to evaluate the effects on soil and/or groundwater guidelines (Marquez et al. 2020a, Todoruk et al., 2023). Modifications to the input parameters leading in changes to the resulting guidelines of at least 10-times, 5- to 10-times, and 1- to 5-times were considered to have a significant, moderate, and limited influence, respectively. Key findings from the sensitivity analysis are summarized in Table 11 and included:

- The Domenico model has higher sensitivity to half-life, fraction of organic carbon (foc; in both fine- and coarse-grained soil), and infiltration rate (in coarse-grained soil) than other parameters, especially at the lower end of the ranges assessed (Marquez et al., 2020a).
- The half-life and infiltration rate inputs into the model that influenced resulting guidelines are directly related to the modelled geometric and flow parameters that could vary across sites.
- Within the model, higher dilution factors correlate directly to higher guideline values. Organic carbon-water partitioning coefficient (Koc) in the model is influenced by foc and half-life. The analysis indicates that the model has moderate sensitivity to Koc, with potential dilution increasing linearly as values increase and foc may influence the overall dilution factors, however, the sensitivity to these parameters is interdependent.
- The model did not show high sensitivity to soil bulk density which directly calculates total porosity, vapour filled- and moisture-filled porosity in the model in the absence of site parameter data. Soil moisture and particle density are modifying factors for bulk density and the estimated porosities and should be further evaluated to refine the model.
- Half-life was generally a sensitive parameter at the lower ends of the included ranges with the largest variation in dilution factors within the 0.25- to 4-year half-life range. The trends observed in outcomes were similar between coarse- and fine-grained soils. **Half-life is generally considered to have a significant influence on soil and groundwater guideline outcomes.**

Table 11. Degree of influence of various parameters on dilution factors within the Domenico Robbins groundwater model for calculating Tier 1 Guideline modifications and Tier 2 Guidelines in coarse-textured soils.

| | **Bromacil (Coarse)** | | | | | **Tebuthiuron (Coarse)** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Half Life (years)** | **foc (g/g)** | **Koc (mL/g)** | **Dry Bulk Density (g/cm³)** | **Infiltration Rate (m/yr)** | **Koc (mL/g)** | **foc** | **Koc (mL/g)** | **Bulk Density (g/cm³)** | **Infiltration Rate (m/yr)** |
| DF1 | Ø | ↑ with increasing foc | ↔ with increasing Koc | ↓ | Ø | Ø | ↑ with increasing foc | ↔ with increasing Koc | ↓ | Ø |
| DF2 | Ø | Ø | Ø | Ø | Ø | Ø | Ø | Ø | Ø | Ø |
| DF3 | Ø | Ø | Ø | Ø | ↑ at low rates | Ø | Ø | Ø | Ø | ↑ at low rates |
| DF4 | ↑ impact at lower half-life range | ↑ with increasing foc | ↔ with increasing Koc | ↓ | Ø | ↑ impact at lower half-life range | ↑ with increasing foc | ↔ with increasing Koc | ↓ | Ø |
| Range Tested | 0.25 to 64 | 0 to 6 | 4 to 157 | 1.0 to 2.0 | 0.001 to 0.5 | 0.25 to 64 | 0 to 6 | 4 to 157 | 1.0 to 2.0 | 0.001 to 0.5 |
| Default Tier 1 | 1,000,000 | 0.005 | 66.6 | 1.7 (coarse); 1.4 (fine) | 0.006 (coarse); 0.012 (fine) | 1,000,000 | 0.005 | 23 | 1.7 (coarse); 1.4 (fine) | 0.006 (coarse); 0.012 (fine) |

DF1 – soil-leachate partitioning; DF2 – transport through unsaturated zone; DF3 – groundwater mixing; DF4 – lateral transport through saturated zone; foc = fraction of organic carbon; Koc = water-organic carbon partition coefficient

Ø indicates no influence; ↑ indicates significant influence; ↔ indicates moderate influence; ↓ indicates limited to no influence

### *3.2.2 Guideline Calculation for Irrigation Water and Freshwater Aquatic Life Pathways*

Water quality guidelines in Canada, exist for the protection of FAL and IW both at the federal and provincial level. Provincial guidelines for Alberta, British Columbia, Saskatchewan, and Manitoba are based on the Canadian Council of Ministers of the Environment (CCME) guidelines which are in turn derived from toxicological data (Litalien et al., 2020). A review of the applicable guidelines (Litalien et al., 2020) indicated:

- The CCME water quality guideline for Protection of Aquatic Life (CWQG-PAL) for both bromacil (5.0 µg/L) and tebuthiuron (1.6 µg/L) was used to develop the Alberta Tier 1 surface water guideline for the FAL pathway.
- The CCME water quality guideline for the protection of agricultural water uses (CWQG-IW) for both bromacil (0.2 µg/L) and tebuthiuron (0.27 µg/L) was used to develop Alberta Tier 1 surface water guideline for the IW pathway.
- Reported toxicity values for several algal and crop species are on the same order of magnitude as the current Alberta surface water quality guideline for bromacil and tebuthiuron suggesting that FAL and IW surface water quality guideline values are not overly conservative, when applicable (see Litalien et al. (2020) for a summary of the literature).
- The 2019 update to the Alberta Tier 1 Guidelines included a time cap consideration on lateral groundwater transport. The influence of the 500-year transportation cap on the soil quality guidelines for the protection of the FAL pathway was investigated and found to have no impact on Guidelines for either fine- or coarse-grained soils.
- The EPA Tier 1 (2023) guidance document does not indicate a half-life, or degradation rate for bromacil or tebuthiuron resulting in an assumption that the chemical does not degrade and the default factor in the model is 1,000,000 years.
- Although bromacil half-life is highly variable in the literature, ranging from 14 to 1,494 days there is strong evidence to suggest that degradation does in fact occur (Litalien et al., 2020). Of the 42 sources reviewed, ten sources reported half-lives of less than 90 days; 30 reported half-lives between 6 months and 1 year; and the most cited half-lives ranged between 120 days and 180 days (Figure 6).
- Although most of the data were generated from experiments conducted under standard laboratory conditions or in field studies conducted in tropical regions, the data confirms degradation occurs.
- Incorporation of a half-life into Tier 2 Risk Assessment Guideline derivation allows for both the FAL and IW pathway guidelines to be raised above laboratory detection limits for bromacil and tebuthiuron.

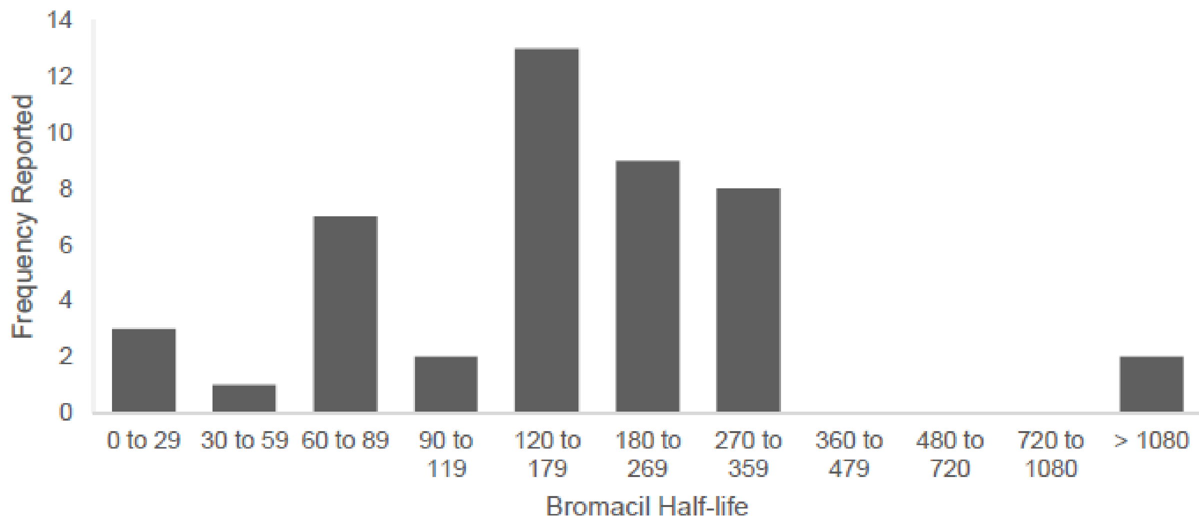



Figure 6. Distribution of bromacil half-life values (days) reported in the literature. Taken from Litalien et al. (2020).

### *3.2.3 Sterilant-specific Model Input Data*

Laboratory studies were developed to refine two of the model input parameters considered sensitive: half-life and partition coefficients for each sterilant (Houston et al., 2020).

#### 3.2.3.1 Half-life Estimation

To estimate half-life, coarse- and fine-grained uncontaminated Alberta soils were spiked with bromacil and tebuthiuron and evaluated in a series of microcosms in varying saturated conditions over 105 weeks (2 years) (Todoruk et al., 2023). Variables included concentration of sterilants (high versus low); weathering (fresh versus aged); presence / absence of chloride; mass / volume of the sample; and source of formulation (Table 12).

Table 12. Experimental parameters for half-life study.

| **Treatments/ Parameters** | **Description and Justification for Treatment/Parameter** |
|---|---|
| Soil type | • Coarse- and fine-grained soil. |
| Contaminant | • Bromacil (Hyvar® X-L) and Tebuthiuron (Spike® 80DF). |
| Commercial Formulation | • To identify whether differences in degradation rates were observed with a commercial formulation as compared to laboratory standards, a "commercial formulation" treatment in coarse-grained soil was added. |
| Concentration | • The high concentration was intended to conservatively reflect fresh application rates (Bromacil – 10 mg/kg; Tebuthiuron – 4 mg/kg).<br>• The low concentration was intended to reflect weathered concentrations without accounting for changes in bioavailability that may accompany weathering (Bromacil – 2 mg/kg; Tebuthiuron – 0.9 mg/kg). |

| Treatments/ Parameters | Description and Justification for Treatment/Parameter |
|---|---|
| Weathering / Aging | • Bromacil contamination is reflective of unweathered and weathered conditions.<br>• Unweathered treatments were spiked with known concentrations of bromacil.<br>• Soils from a site with field-weathered bromacil were included.<br>• Field-weathered tebuthiuron-impacted soils were not included as sites were not identified where tebuthiuron was the only contaminant of concern in soils. |
| Salinity | • 2,500 mg/kg chloride (similar order of magnitude to chloride levels found in Houston et al. (2020)). |
| Mass / Volume | • To identify whether the mass of soil and volume of incubation jar influenced degradation rates, a "bulk incubation" treatment in coarse-grained soil was added to the experiment. The bulk incubation setup had the same ratio of soil volume to headspace volume as the primary experiment (one replicate). |
| Soil Moisture | • Intended to be reflective of Alberta subsoil conditions – suboptimal moisture percentages were selected (12% for fine-grained; 7% for coarse-grained) |
| Temperature | • Intended to be reflective of Alberta subsoil conditions – experimental conditions were maintained at 5°C. |
| Controls | • Unspiked for bromacil and tebuthiuron for each soil type. |

Key findings from the study were:

- Data analysis and visualization of the experimental half-life data indicated degradation of bromacil and tebuthiuron was generally limited under the experimental conditions investigated (i.e., cool temperatures (4 to 5°C; fine-grained soil or coarse-grained soil; high or low concentrations), though did occur.
- A significant *decrease* in sterilant concentrations was found for ***bromacil*** in the ***low concentration*** (2 mg/kg) treatment in combination with ***fine soil***, although the effect size was minimal, and the overall results imply **very slow degradation**.
- When initial *bromacil* concentrations were *high* (10 mg/kg) no meaningful signal of degradation can be estimated from the measured data for either *fine- or coarse*-textured soil.
- No meaningful signal of degradation can be estimated from the measured data for *tebuthiuron* in either concentration or soil treatment.

Limited, or slow degradation, for soil sterilants is aligned with the literature. Litalien et al. (2020) conducted a literature review and sensitivity analysis on bromacil and tebuthiuron half-lives. While over 50 peer reviewed papers report on the dissipation, migration and or half-lives of sterilants, only a limited number of the studies were from temperate climates or under controlled temperatures in the lab, and the majority were conducted on surface soil (i.e., <1.5 m below ground surface). According to the literature reviewed by Litalien et al. (2020), bromacil half-lives from the relevant studies ranged between 60 and 270 days with cooler temperature, drier climates, and higher soil organic carbon content having been noted as major drivers resulting in slower degradation. This is aligned with the experimental results from the half-life experiments which demonstrated slow degradation under cool temperatures.

Similarly, half-lives reported in the literature for tebuthiuron are variable ranging from days to >8 years, with the majority reported as less than 1 year with significant influences from temperature and annual precipitation. Few studies are available with directly applicable degradation estimates or half-lives for tebuthiuron in northern climates, though the data available does confirm degradation occurs, albeit slowly.

The EPA Tier 1 (2023) guidelines are based on a highly conservative approach which does not indicate a half-life, or degradation rate for bromacil or tebuthiuron (defaults to > 1,000,000 years) resulting in soil quality guidelines for FAL and IW pathways below laboratory method detection limits. Inclusion of a half-life for bromacil and tebuthiuron has meaningful impacts on the Soil Quality Guidelines for the FAL and IW pathways, while still ensuring the appropriate level of protection to receptors, particularly when initial soil concentrations are low. Although the estimated half-lives observed in the laboratory experiments are subject to uncertainties, when combined with literature data and field observations, there is weight of evidence to suggest that a half-life, however conservative, should be included in Tier 2 Guideline development. Based on these results, the following is recommended:

- When sites are identified with **fine-textured soils** and **low initial starting concentrations** of **bromacil** (~2 mg/kg) a conservative half-life value could be applied when using a Tier 2 Risk Assessment approach.
  - A half-life of 10 years is recommended for Tier 2 applications under specific site conditions (i.e., fine-textured soils with low initial concentrations of bromacil). A value of 10 years provides a conservative degradation rate based on experimental results for low initial concentrations and is greater than half-lives reported in the literature under all environmental conditions.
  - Additional experimentation is recommended to refine degradation rates for inclusion in Tier 2 risk assessment, particularly for tebuthiuron. Further study is required to determine the initial concentration recommendations for bromacil and tebuthiuron in coarse- and fine-textured soils.

#### 3.2.3.2 Partition Coefficients

The water-organic carbon partition coefficient, Koc, a partition coefficient normalized to the soil's organic carbon content, is generally used to provide an indication of the mobility of a compound in soil with a value less than 100 indicating that a compound is very mobile (Branham et al., 1995). The current EPA Tier 1 document includes Koc values of 66.6 mL/g and 23 mL/g for bromacil and tebuthiuron, respectively. These values are sourced from the Oak Ridge National Laboratory Risk Assessment Information System which in turn uses values from the US EPA EPI (Estimation Programs Interface) Suite. Thus, the Koc values used in the EPA Tier 1 guidelines are based on chemical estimation methods, rather than on measured data. Accordingly, a program was initiated to measure the Koc for these two chemicals.

A modified Tier 2 OECD #106 [*Guideline for the Testing of Chemicals: Adsorption-Desorption Using a Batch Equilibrium Method*] assessment, utilizing three soils rather than five, was used to develop adsorption isotherms based on the organic carbon content of uncontaminated Alberta subsoils (Bachmann and Tindal, 2023b). Measured parameters in the laboratory study conducted included water-organic carbon partition coefficient (Koc) and sorption distribution coefficient (Kd) for bromacil and tebuthiuron in soils with variable texture and total organic carbon (TOC) (Table 12) (Bachmann and Tindal, 2023b).

Study results indicated:

- Sorption of bromacil and tebuthiuron is complex and dependant on multiple factors.

- Adsorption of bromacil was higher in all three soils investigated experimentally than tebuthiuron, as expected based on published $K_{oc}$ values and chemical formula.
- Greater adsorption occurred in fine-grained soil compared to coarse-grained soil which may be attributable to higher organic carbon measured in the fine-grained soils and/or lower porosity that can restrict migration of organic contaminants.
- Experimental data were inconclusive to inform defensible Koc values for bromacil and tebuthiuron in Alberta coarse- and fine-textured soils. However, further investigation or experimentation to confirm Koc's relevant to the Alberta context is not recommended based on further literature and model sensitivity analysis:
    - The Koc value for bromacil (66.6 mL/g) used in the development of bromacil Tier 1 screening guidelines using the Domenico model (AEP, 2019) is slightly higher than the most cited value range (30 to 40 mL/g) (Litalien et al., 2020). The soil quality guideline for the protection of the FAL pathway is moderately sensitive to changes in Koc's for Bromacil, however the IW pathway was not very sensitive.
    - The Koc value for tebuthiuron (23 mL/g) used in the development of Tier 1 screening guidelines is less than the most cited value (80 mL/g) (Litalien et al., 2020) in the literature.
- Finer textured and higher TOC soils had higher distribution coefficients (Kd values) than coarse-textured and low-TOC soils for both sterilants; Kd values were consistent with sterilant concentrations in the soil.
    - Insufficient data was generated through experimentation to inform defensible recommendations for sorption coefficients in guideline calculations. Further investigation is recommended both through literature review of Kd/Foc relationships and experimentation.

#### *3.2.4 Alternative Model Evaluation*

Alternative risk models were evaluated that could be used to derive soil and groundwater guidelines for bromacil and tebuthiuron that would be both protective of the irrigation water (IW) and freshwater aquatic life (FAL) pathways (Litalien et al., 2020). A literature review was conducted to identify scientifically robust models that could be used to assess the transport of bromacil and tebuthiuron through variably saturated media. Thirty models were reviewed and ranked based on their defensibility, applicability, availability, ease of use, and inclusion of novel features relative to the current Tier 2 model.

Three models were selected for a detailed mechanistic review and model analysis based on standard Tier 1 input values and parameters derived from the literature when necessary. Results of the analysis indicated that none of the models reviewed could effectively replace all elements of the Tier 2 model however they could be useful supplements:

- BIOSCREEN is a US EPA model that could be substituted for the current saturated transport component of the Tier 2 model. It follows similar principles to the Tier 2 model but also considers source depletion and as a result, can produce less conservative soil and groundwater guidelines for the FAL pathway.
    - Groundwater quality guidelines (GWQGs) and soil quality guidelines (SQGs) generated by BIOSCREEN for the FAL pathway were generally higher than those generated by the Tier 2 model and all guidelines were above detection limits.

  - BIOSCREEN may be a suitable alternative or supplemental model that would integrate well with the current Tier 2 model. However, BIOSCREEN can only be used for the FAL pathway as unsaturated transport is not considered.
- PWC is a US EPA transport model designed specifically for agrochemicals and can be used to evaluate transport to groundwater. The results of the model analysis showed that the PWC model would produce guidelines like the current Tier 2 model however PWC is more challenging to use than the Tier 2 model and requires many input parameters that may not be readily available for all sites. However, its more detailed approach could be of benefit on a site-specific basis. PWC does not consider lateral transport and thus cannot be used for the FAL pathway, however it does consider runoff to surface water bodies which may be of interest at certain sites.
  - Soil Quality Guidelines (SQGs) for the IW pathway produced by the model were similar if slightly more conservative than those of the Tier 2 model.
  - Given the similarity of the results to the Tier 2 model coupled with the significant increase in complexity, the PWC model is not suggested for most scenarios. However, this model appears to be more sensitive to some soil and hydrogeological parameters (e.g., surface runoff) and thus sites where these factors vary significantly from the typical conceptual site model could benefit from the application of this model.
- PEARL is a European agrochemical transport model that can model transport through both the unsaturated zone and the flux of solutes to surface water bodies. The model proved to be challenging to employ and required values for several parameters that were not readily available but did produce a host of outputs (including upward and downward migration, solute accounting between soil, water, and gas phases, as well as advanced water balances) that could be of interest on a site-specific basis.
  - SQGs for the IW pathway were approximately twice as conservative as those of the Tier 2 guidelines.

#### *3.2.5 Degradation Mechanisms and Metabolites*

A literature review investigating mechanisms and resultant metabolites of aerobic biodegradation, anaerobic biodegradation, and metabolism by flora and fauna was completed to identify degradation processes and metabolites of bromacil and tebuthiuron in soil (Marquez et al., 2020b). The purpose of generating a better understanding of degradation process and mechanisms and potential metabolites was to use the information for potential field screening technologies and to inform risk management and remediation plans or monitoring activities targeting exposure pathways for which risks are predicted. For example, if metabolites could be identified, it could be demonstrated that degradation is occurring, providing lines of evidence for risk management strategies. Findings included:

- Nine bromacil and eight tebuthiuron degradation products and their associated degradation processes were identified from laboratory studies (Appendix B).
- No chemical-specific information related to the metabolites was identified (e.g., relevant toxicity data).
- Degradation and metabolism processes included aerobic and anaerobic biodegradation in soil and water, hydrolysis, photodegradation in soil and water, mammalian metabolism, and plant metabolism.

- In general, bromacil and tebuthiuron, as well as their metabolites, were characterized as having low soil adsorption; low volatility; low susceptibility to decomposition by sunlight in soil; low susceptibility to chemical degradation; and low susceptibility to microbial decomposition. Photodegradation in waters may occur more rapidly than in soil based on laboratory estimated half-lives.
- Metabolites were not identified in samples analyzed from the half-life or Koc experiments.

### 3.3 Sterilant Toxicity to Native Plants

Ecological direct contact guidelines for soil sterilants in the Tier 1 Guidelines have been developed using agronomic species which may differ in their sensitivity to soil sterilants compared to native species. Toxicity of bromacil and tebuthiuron to typical Alberta native grassland vegetation species can be used to develop revised direct soil eco-contact guidelines for non-agricultural areas of the province.

Toxicity tests were conducted in a greenhouse study using modified Environment Canada test methods with various native grass species (northern wheatgrass (*Agropyron dasystachyum*), blue grama (*Bouteloua gracilis)*, plains rough fescue (*Festuca hallii)*, June grass (*Koeleria macrantha)*, green needle grass (*Nassella viridula)*, and Western wheatgrass (*Pascopyrum smithii*)) exposed to either bromacil or tebuthiuron in soil sourced from the brown soil zone in Alberta (Thacker, 2021). The study only focused on fine-textured soil, therefore no recommendations were made for coarse-textured soils.

Generally, the species tested tended to be more sensitive to bromacil than tebuthiuron. Inhibition concentration (ICp) values for each endpoint from each species/sterilant test were generated and used to develop species sensitivity distributions and to propose alternate soil quality guidelines for the ecological direct soil contact pathway for fine-textured soil. The study found that *K. macrantha*, *F. hallii*, and *N. viridula* were generally the most sensitive to bromacil; *F. hallii*, *A. dasystachyum*, and *N. viridula* were generally the most sensitive to tebuthiuron. Data generated from the SSP (Litalien and Tindal, 2021 and Thacker, 2021) were combined with historical data used in the development of Tier 1 Guidelines (Stantec Consulting Ltd., 2008, 2012) to produce alternate guidelines recommendations for land use based on the applicable data sets (Table 13). For example, alternate guidelines for natural land use are based on the native plants and invertebrate data, guidelines for agricultural land use are based on the agronomic plants and invertebrate data, and the complete dataset was used for residential, commercial, and industrial land uses. Table 13 summarizes the alternative guidelines, with the caveat that there was not sufficient data for the agronomic plants and invertebrate data set. In most cases, the alternate guidelines were more conservative.

Table 13. Potential alternate ecological direct contact surface soil quality guidelines for fine-textured soil.

| | **Guideline** | **Natural** | **Residential** | **Agricultural** | **Commercial/Industrial** |
|---|---|---|---|---|---|
| **Bromacil** | Current Tier 1 (mg/kg) | 0.20 | | | 0.49 |
| | Alternate[1] (mg/kg) | 0.014 | 0.028 | 0.37 | 0.21 |
| **Tebuthiuron** | Current Tier 1 (mg/kg) | 0.046 | | | 0.60 |
| | Alternate[1] (mg/kg) | 0.023 | 0.018 | 0.018 | 0.15 |

Table adapted from Litalien and Tindal (2021).

[1] Based on an expanded dataset which includes more native plant species than the current Tier 1 guidelines.

## 3.4 Knowledge Gaps and Recommended Practices

### *3.4.1 Knowledge Gaps Associated with a Risk-Based Approach to Management of Sterilant Impacted Sites*

Knowledge gaps associated with chemical-specific parameters used in risk assessment and modeling remain. Further knowledge generation is required for half-life, soil sorption coefficients and sterilant toxicity to inform defensible recommendations for use in Tier 2 Guideline modifications. Recommendations for further study include:

Half-life and Sterilant Degradation

- A full asymptotic decline in degradation rates was not observed in treatments / replications during the SSP half-life experiments indicating the need for longer-duration half-life experiments.
    - Additional literature meta-analysis is recommended to correlate half-life with temperature, moisture content and organic carbon. Data analysis was based on half-life ranges rather than individual half-life values which could inform a defensible conservative degradation rate, particularly for bromacil.
    - Additional experimentation is recommended to refine degradation rates for Alberta conditions for inclusion in Tier 2 risk assessment, potentially in larger batch-scale vessels to allow ongoing sampling from a single bulk source for the duration of experiment, particularly for tebuthiuron.
    - Further study is required to determine the influence of initial concentration of bromacil and tebuthiuron on degradation rates in coarse- and fine-textured soils.

Partition Coefficient

- Insufficient data was generated through experimentation to inform defensible recommendations for alternative sorption coefficients in guideline calculations.
    - Further investigation is recommended both through literature review and experimentation.
        - Extract Kd/foc data points from literature and conduct a meta-analysis to inform Koc values for both bromacil and tebuthiuron.

Sterilant toxicity

- Test toxicity with a range of native species in a coarse-grained soil (Thacker (2021) focused on fine-grained soils) and species from other ecological zones (Thacker (2021) focused on native grassland species).
- Test toxicity with a range of native species grown in soils with varying chemical and physical properties from within Alberta to give a more complete picture of the range of effects sterilants may have on native plants.

### *3.4.2 Recommendations for a Risk-Based Approach for Management of Sterilant-impacted Sites*

A summary of recommended practices and opportunities for improved risk assessment and management of bromacil- and tebuthiuron-impacted sites is provided below. Figure 7 shows considerations for practical application of the information.

- Compare Phase 1 and 2 ESA and CSM to Tier 1 Guidelines as a first step to determine management options.
    - Practitioners should plan to assess groundwater when bromacil or tebuthiuron are present; install groundwater monitoring wells during the initial Phase 2 ESA in areas representative of "worst-case" scenario.
- Determine the most limiting applicable exposure pathway based on Tier 1 Guidelines. Compare worst case groundwater concentration to Irrigation Water (IW) and Freshwater Aquatic Life (FAL) surface water.
    - Groundwater < guideline = applicable guideline will be ecological soil contact guideline.
    - Groundwater > guideline = Tier 2 approach recommended.
- Exclude pathways where applicable and determine if additional site-specific non-chemical-specific data (Db, foc, porosity, etc.) or chemical-specific parameters (half-life, Koc) would be beneficial for calculation of modified Guidelines through a Tier 2 approach.
    - Exclude FAL pathway if no surface water bodies are present within 300 m by (1) assessing the groundwater and monitoring sterilant plume characteristics; and (2) applying a conservative degradation half-life justified through literature or site-specific data.
    - Exclude IW pathway if outside agricultural regions.
- Consider where the site is located and if agronomic or native species are intended for reclamation.
- To reduce risk to receptors, if equivalent land capability requires native grass species for reclamation consider using the alternate soil quality guidelines for Tier 1 ecological direct contact surface soil quality guidelines for fine-grained soil in non-commercial and non-industrial land uses (Thacker, 2021).

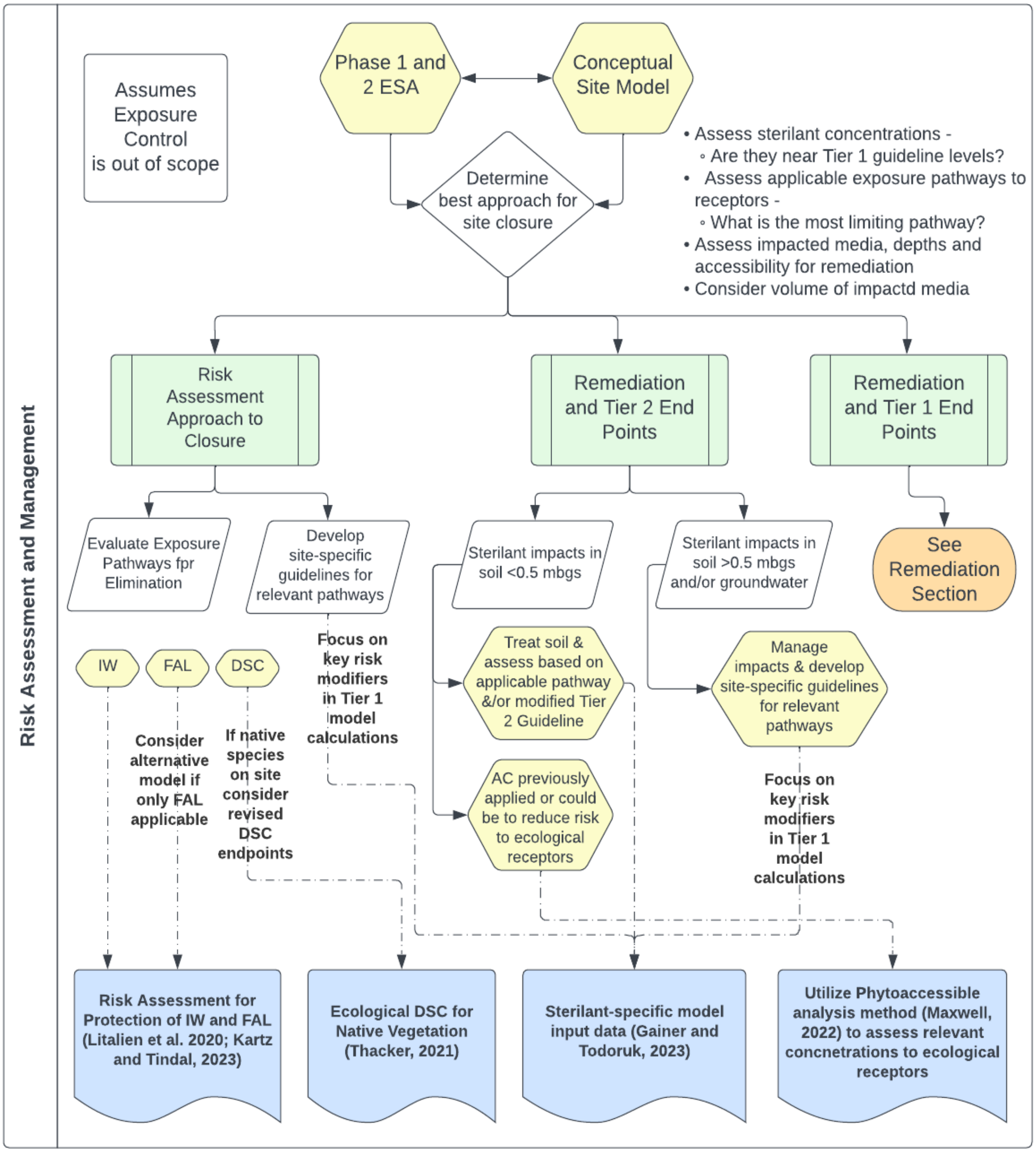



Figure 7. Considerations for application of the Tier 1 and 2 Risk Assessment Approaches for more effective management of sterilant impacted sites.
ESA – environmental site assessment; IW – irrigation water pathway; FAL – freshwater aquatic life pathway; DSC – direct soil contact pathway

# 4.0 REMEDIATION

## 4.1 Problem Statement

Several challenges were identified associated with remediation of sterilant-impacted sites including:

- Long-term evaluations of remediation treatment longevity, which is particularly relevant for immobilization treatments that rely on sterilant adsorption, are not available.
- Detailed, publicly accessible data on operational-scale treatment demonstrations in Alberta (e.g., target sterilant(s) and concentrations, co-contaminants, methods, rates, and costs) are not available.
- Information on the potential for, and value of, combining treatment technologies to increase remediation success is lacking.

The SSP addressed these challenges by investigating commercial-ready and near-commercial technologies for their suitability for remediation of bromacil and tebuthiuron (Figure 8).

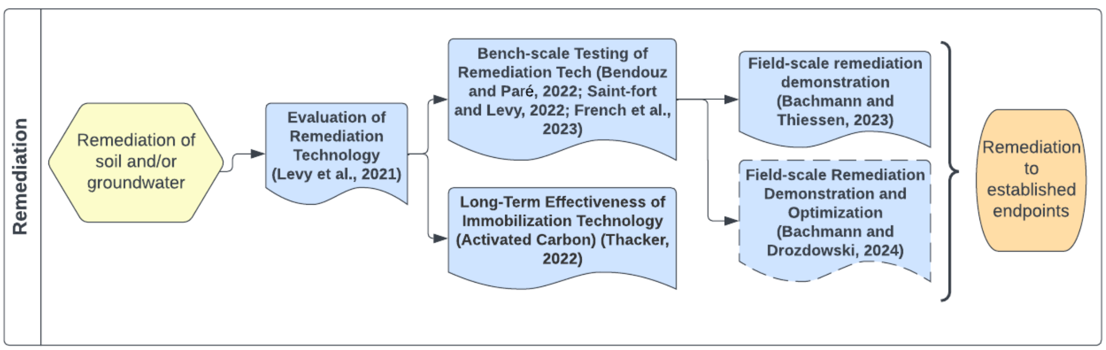



Figure 8. Remediation projects.

## 4.2 Evaluation of Remediation Technologies

Potential sterilant remediation technologies were evaluated to determine their applicability to Alberta conditions and specific site challenges, while also considering cost, logistics of application, and sustainability. In addition, a review of applicable site types and industry challenges was completed and high-potential technologies that could be de-risked at bench- and meso-scale testing stages, prior to field-scale evaluation were identified.

Technologies were split into four treatment types: (1) Ex-situ soil remediation technologies, (2) In-situ soil remediation technologies, (3) Ex-situ water remediation technologies, and (4) In-situ water remediation technologies (Levy et al., 2021). Typical remediation costs, where available, were identified. Technologies were ranked as:

1. ***Proven*** for treatment of sterilants – requires no further evaluation unless providers can identify explicit requirements for testing to significantly refine the process.
2. ***Impractical*** for application for reasons as specified (e.g., low effectiveness and/or longevity, elevated cost, or potential residual impacts to treated media, such as incomplete remediation resulting in harmful daughter products or impact to soil quality).
3. ***Potential*** to evaluate through bench-, meso-, pilot- or field-scale trials, pending additional review and prioritization.

In addition, for practical application, treatment options needed to consider: (1) a range of endpoint concentrations based on different site requirements, (2) sterilant (bromacil or tebuthiuron or both), and (3) soil type (i.e., coarse- or fine-grained; specific organic matter content). Table 14 provides a summary of the technologies evaluated and their applicability to sterilant impacted sites.

Table 14. Ex-situ and in-situ soil and water remediation technologies evaluated. From Levy et al. (2021).

| Technology Type | Proven | Impractical | Potential |
|---|---|---|---|
| Ex-situ Soil Remediation Technologies | • Immobilization (with Activated Carbon)<br>• Remedial Excavation and Disposal<br>• Thermal Desorption | • Landfarming, Bio-piles and Composting<br>• Slurry Bioreactors<br>• Soil Washing | • N/A |
| In-situ Soil Remediation Technologies | • Immobilization (with Activated Carbon) | • Bioremediation and Natural Attenuation<br>• Enhanced Microbial Degradation<br>• Enzymatic Remediation<br>• In-situ Thermal Remediation<br>• Phytoremediation<br>• TRIUM SRT – Immobilization / Stabilization<br>• Fertilizers<br>• Manure/ Organic Amendments<br>• Soil Flushing | • Activated Carbon Slurry<br>• Chemical Oxidation<br>• Chemical Reduction<br>• Electrokinetic Remediation |
| Ex-situ Water Remediation Technologies | • Activated Carbon Filtration<br>• Chemical Oxidation and Reduction<br>• Deep Well Injection<br>• Photocatalysis | • Chlorination<br>• Electro/Photoelectron Fenton Processes<br>• Nanofiltration/Reverse Osmosis<br>• Photoelectrocatalysis using $WO_3$ and $H_2O_2$, $H_2SO_4$, and $H_2O_2$ as supporting electrolyte<br>• Synergistic Vacuum Ultraviolet / Chlorine Process | • N/A |

| Technology Type | Proven | Impractical | Potential |
|---|---|---|---|
| In-situ Water Remediation Technologies | • N/A | • Bioremediation<br>• Phytoremediation<br>• Sorption + AOP with Micron Trap-Ox Zeolites FeBEA35 and $H_2O_2$ | • Activated Colloidal Carbon Slurry + ChemOx<br>• Enhanced Biodegradation<br>• Permeable Reactive Barrier (PRB) with Embedded Reductant<br>• Surfactant-Enhanced Removal |

N/A = Not Applicable

The study found there are a variety of treatment options available but limited experience in their implementation for treatment of sterilants in Alberta (Levy et al., 2021). Thermal desorption was the only ex-situ remediation technology previously proven and remains a viable option for management of sterilant impacted sites. Immobilization remediation technology (i.e., activated carbon) was prioritized for laboratory experimentation and destructive remediation technologies ranked as "potential" (Table 14) were prioritized for further testing at bench-scale prior to field-scale demonstration. Concurrent as well as sequential treatments were also identified as opportunities to address sterilant-impacted sites that warrant further investigation.

### 4.3 Immobilization Technologies for Management of Sterilant Impacted Sites

Activated carbon (AC) has long been considered one of the most effective in-situ remediation technologies for soil sterilants, adsorbing sterilants to immobilize them, thus preventing uptake by plants or leaching through the soil. However, there is hesitation from a regulatory perspective to accept immobilization as a long-term solution for managing sterilant-impacted soils due to uncertainty regarding the longevity of immobilization. Table 15 summarizes the literature review results.

Table 15. Factors influencing Activated Carbon (AC) sorption in soils.
Literature review findings from Thacker (2022).

| Literature Review Component | Review Findings |
|---|---|
| Potential for AC to degrade over time | • Black carbon[2] can degrade and change in structure over time, and sorption dynamics can also change.<br>• AC can be relatively stable over time (i.e., five years) and AC is likely more stable than biochar, given its higher charring temperature.<br>• While AC is recalcitrant in soil, weathering processes have the potential to degrade AC and change sorption dynamics over time; the extent of this change has not been evaluated under Alberta conditions. |

[2] Black carbon refers to carbon-rich material derived from incomplete combustion of vegetation and fossil fuels, as well as mineral weathering – biochar and AC are forms of black carbon.

| Literature Review Component | Review Findings |
|---|---|
| Factors influencing sorption and desorption | • Sterilant sorption is dependant on clay and organic matter (OM) content:<br>  ○ Bromacil – absorbed more strongly by OM than clay and more likely to be found at the surface in soils with ↑ OM.<br>  ○ Tebuthiuron – leaching is lowest in soils with high clay or OM.<br>• Desorption of sterilants can be affected by pH and temperature, though OM has the most influence.<br>  ○ Alberta soils are generally well buffered; therefore, pH is not likely to be a driving factor in sorption dynamics.<br>• Co-contaminants compete for adsorption sites on AC.<br>• Solubility of sterilant and co-contaminant impacts likelihood to sorb and stay sorbed.<br>  ○ Compounds with ↓ solubility = ↑ likelihood to sorb therefore influencing sterilant immobilization. |
| Weathering | • Aging factors influencing AC degradation include biological (exposure to nutrients and microorganisms), thermal/chemical (exposure to high temperatures), physical (exposure to freeze-thaw cycles).<br>• Abiotic factors have the greatest influence on sorption dynamics:<br>  ○ Exposure to high temperature influenced physiochemical properties of AC which resulted in ↑ desorption.<br>  ○ Freeze-thaw cycles ↓ effectiveness of AC. |

No suitable sites could be found with sufficient information about AC application rates and sterilant concentrations to inform research questions related to long-term immobilization of sterilants by AC. Therefore, a laboratory study was conducted focused on understanding how and where the technology could effectively be applied in Alberta and aimed to support decision making regarding the applicability of AC as a remediation technology with sound science (Thacker, 2022). Laboratory work was informed by the literature review (Thacker, 2021) and conducted to assess:

1. The percentage of each sterilant retained by AC (based on desorption experiments via modified Synthetic Precipitation Leaching Procedure (SPLP)).
2. The longevity of sterilant immobilization by AC compared with soil that was not amended with AC (based on an artificial weathering experiment using multiple freeze-thaw cycles of sterilant-spiked topsoil).
3. Phyto-accessible sterilant concentrations pre- and post-weathering compared to total sterilant concentrations.

The results of the studies are summarized in Table 16. In general, phyto-accessible concentrations of bromacil and tebuthiuron were below Tier 1 Direct Soil Contact (DSC) Guidelines after weathering when soils were amended with AC (and below Tier 1 Soil Guidelines for many samples). It is difficult to extrapolate the results to the long-term sorption stability as there are other processes that may influence stability over time however, based on the artificial weathering study, it is interpreted that AC effectively sorbs the majority of bromacil and tebuthiuron over time. It was noted that bromacil and tebuthiuron behaved differently, indicating sterilant-specific approaches to AC treatment are required. It was recommended to include AC as a remediation technology in meso- or field-scale demonstrations to develop best practices for use of AC as an immobilization remediation technology.

Table 16. Summary of research from the immobilization studies.
From Thacker (2022).

| Parameter and Purpose of Inclusion | Experimental Results and Interpretation |
|---|---|
| Desorption: Sterilant immobilization and phyto-accessibility<br><br>Designed to simulate worst-case scenario of sterilant leaching in soil and assess the percentage of each sterilant retained by AC | • Sterilant desorption in the presence of AC was significantly lower than without AC for all treatments.<br>• Desorption ranged from 0% to 14% in AC-amended soil, with higher desorption in coarse-grained soil compared to fine-grained soil.<br>• Initial sterilant concentration did not have a strong influence on amount of sterilant desorbed.<br>• Phyto-accessible fraction in soils amended with AC was much lower compared to the non-amended soil, indicating that the sorption of sterilants to AC reduced phyto-accessibility.<br>• Phyto-accessible fraction was typically greater than the desorbed fraction in AC amended soils, indicating that a portion of the sterilants present may be available to plants but may not readily desorb from AC.<br>• In the absence of weathering, total bromacil and tebuthiuron concentrations were significantly lower in AC-amended soil. This indicates that the laboratory method used to extract "total" sterilants may not be sufficient when a strong sorptive material, such as AC, is present in soil. |
| Weathering: Freeze-thaw cycles used to artificially weather AC and sterilants to assess the longevity of sterilant immobilization by AC | • In soil not amended with AC, phyto-accessible bromacil increased significantly with weathering.<br>• In topsoil, desorption ranged from 1% to 3% after weathering of AC-amended soil; however, there were cases where the phyto-accessibility was increased after weathering, though still below levels in soils without AC.<br>• AC amendment significantly lowered phyto-accessible sterilant concentrations, in many cases below Tier 1 Guidelines, indicating that a majority of the sterilants remained sorbed to AC after physical weathering (phyto-accessible bromacil concentrations depicted in Figure 9).<br>• Changes in phyto-accessibility with weathering differed for tebuthiuron compared to bromacil.<br>• AC was effective at immobilizing soil sterilants when applied at a rate of 400:1 (AC:sterilant, weight basis) with significantly lower sterilant leaching in soil amended with AC compared to non-amended soil. |

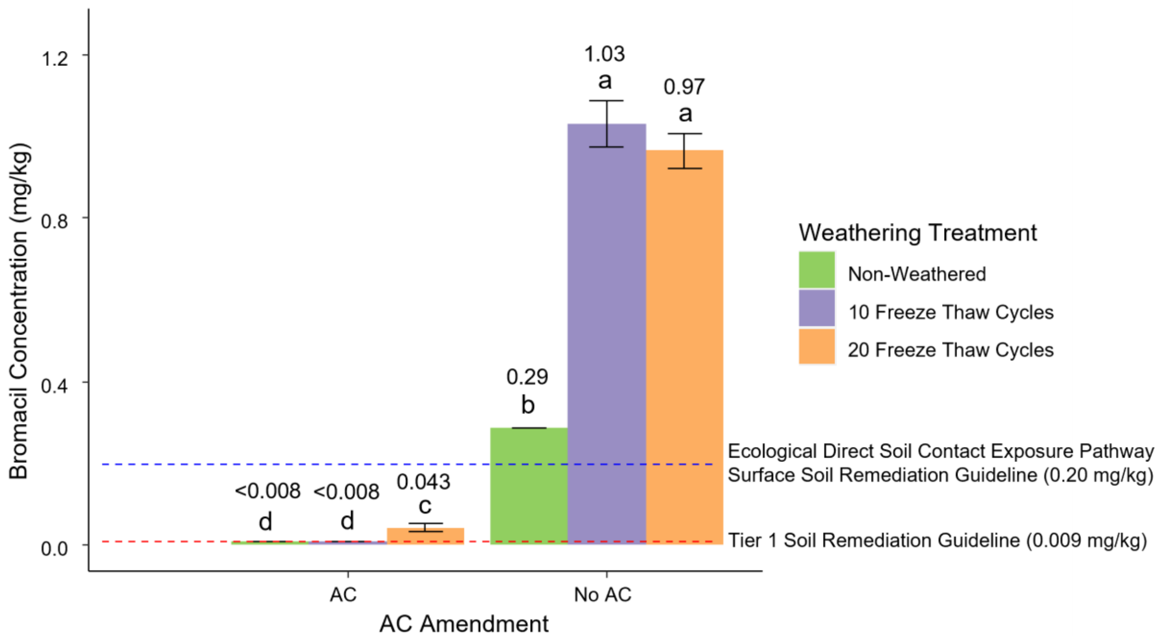



Figure 9. Phyto-accessible bromacil concentration in soil amended with activated carbon (AC) or not amended (no AC).
From Thacker (2022).
The two AC amendment treatments were exposed to three different weathering treatments: no weathering, 10 freeze-thaw cycles, or 20 freeze-thaw cycles. Bars represent means (n=3), and error bars indicate the standard error. Average values are provided above each bar. Different lowercase letters indicate significant differences among the treatments.

### 4.4 Bench-scale Evaluation of Destructive Remediation Technologies

Based on the remediation technology evaluation and interviews with technology providers and practitioners (Levy et al., 2021), a two-stage bench-scale testing program evaluated promising destructive remediation technologies to assess their potential for field-scale trials:

- In-situ chemical oxidation (ISCO) and reduction (ISCR) technologies (Bendouz and Paré, 2022):
  - DARAMEND® (ISCR),
  - Potassium persulfate (activated with hydrated lime) (ISCO),
  - Sodium persulfate (activated with calcium peroxide) (ISCO),
  - Sodium persulfate (activated with sodium hydroxide) (ISCO),
  - Hydrogen peroxide ($H_2O_2$) (utilising VTX catalyst) (ISCO),
- Trap & Treat® BOS 200+® (ISCO), Trap & Treat® CAT 100 (ISCO), Micro-scale Zero Valent Iron (ZVI) (ISCR) (French et al., 2023), and
- Electrocoagulation (Saint-Fort and Levy, 2022).

Several surfactants were evaluated for their ability to enhance the rate of contaminant destruction when combined with ISCR and ISCO (Bendouz and Paré, 2022). Table 17 summarizes the technologies and bench-scale test results.

Table 17. Summary and results of technologies selected for bench-scale remediation testing.

| Technology | Technology Summary | Bench-Scale Test Results* |
|---|---|---|
| DARAMEND® (ISCR) | • Composed of a controlled-release organic carbon substrate combined with zero valent iron (ZVI).<br>• Requires strongly anaerobic (saturated) conditions to maintain reducing conditions; requires incorporation (generally with specialized rotary tillers).<br>• Native microorganisms in the soil use the carbon and nutrients provided by DARAMEND® to drive the oxidation reduction potential (ORP) down. Corrosion of the iron, as intended, further reduces the ORP creating conditions for contaminant destruction.<br>• Primarily selected for treatment of bromacil. | • 2 dosing rates (1% and 3%), with and without tilling at 30 days, with and without TWEEN 80 surfactant.<br>• Highly effective in the treatment of bromacil (98% reduction using 3% dosage without tilling; 97% reduction using 1% with tilling @ 30 days) (Bendouz and Paré, 2022).<br>• Sterilant destruction was obtained without tilling the sample after a 30-days contact time indicating a single pass application with appropriate wetting conditions could achieve remedial objectives.<br>• Benefit of surfactant (TWEEN) application was inconclusive.<br>• Lowest overall cost for application ($55/MT soil (product only) using a 1% w/w loading rate).<br>• DARAMEND® will only work in saturated (or high-water content soil conditions (90% water holding capacity)) as contaminant destruction pathway will be ineffective if water content is insufficient.<br>• Deemed unlikely to be effective in treating tebuthiuron due to absence of evidence that it degrades anaerobically.<br>• Recommended to test lower DARAMEND® dosage rates (0.25% or 0.5% w/w given sufficient soil moisture and contact time). |
| Potassium persulfate activated with hydrated lime (ISCO) | • Treatment provides a long-term (i.e., 1 to 3 year) chemical oxidation environment based on low solubility of both oxidant and activator.<br>• Persulfate releases minimal gas upon reaction and has a relatively low Soil Oxidant Demand compared with other ISCO amendments.<br>○ These properties, combined with longer persistence, are ideal for lower permeability soil and bedrocks.<br>• This blend of oxidant and activator also has minimal reactivity with carbon steel or concrete underground infrastructure. | • Stage 1 Testing<br>○ Low, medium, and high dose for both bromacil and tebuthiuron.<br>○ Oxidant and alkaline activator added together and incubated for 30 days; preliminary screening did not include surfactants.<br>○ Minimal reduction in bromacil or tebuthiuron concentration (Bendouz and Paré, 2022).<br>○ Technology not selected for Stage 2 testing. |

| Technology | Technology Summary | Bench-Scale Test Results* |
|---|---|---|
| Sodium persulfate activated with calcium peroxide (ISCO) | • Treatment consisted of 50% sodium persulfate and 50% calcium peroxide, with the sodium persulfate portion leading to the chemical oxidation of contaminants in aqueous phase within the soil matrix.<br>• Oxidation time for this technology is typically between 4 to 12 weeks.<br>• Calcium peroxide lasts 3 to 6 months and promotes aerobic biodegradation when soils are sufficiently but not excessively moistened. | • Stage 1 Testing<br>○ Low, medium, and high dose for both bromacil and tebuthiuron.<br>○ Oxidant and alkaline activator added together and incubated for 30 days; preliminary screening did not include surfactants.<br>○ Minimal reduction in bromacil or tebuthiuron concentration (Bendouz and Paré, 2022).<br>○ Technology not selected for Stage 2 testing. |
| Sodium persulfate activated with sodium hydroxide (ISCO) | • Provides 4 to 12 weeks of active chemical oxidation of the target contaminant per application event. However, with both products containing sodium, soil and aquifer impacts may occur and this approach should only be taken when sodium and sodium adsorption ratios (SAR) at a site can accommodate additional sodium.<br>• Sodium persulfate releases minimal gas and has a relatively low Soil Oxidant Demand. This, in addition to relatively long persistence, is ideal for lower permeability soil and bedrock.<br>• Components are both fully soluble and can be pre-mixed at the surface before application and sprayed as a true aqueous solution. | • Stage 1 Testing<br>○ Low, medium, and high dose for both bromacil and tebuthiuron.<br>○ Oxidant and alkaline activator added together and incubated for 30 days; preliminary screening did not include surfactants.<br>○ 76% reduction in tebuthiuron concentration at low dosage application (Bendouz and Paré, 2022).<br>○ Technology selected for Stage 2 testing with surfactants.<br>• Stage 2 Testing<br>○ Included surfactant CHEMSOL DL4 (for bromacil) and DECONIT (for tebuthiuron).<br>○ 80% reduction in tebuthiuron concentration at low dosage application; determined that surfactant did not improve degradation enough to warrant inclusion.<br>○ Recommended for tebuthiuron treatment without surfactant. |

| Technology | Technology Summary | Bench-Scale Test Results* |
|---|---|---|
| Hydrogen peroxide ($H_2O_2$) alone or activated using VTX (catalyst) (ISCO) | • Provides 2 to 4 weeks of chemical oxidation per application event.<br>• Residual oxygen released from the $H_2O_2$ decomposition could promote biological degradation of the contaminants once the oxidation phase is completed.<br>• Peroxide degradation by-products are water, oxygen, and carbon dioxide, thus not adding any salt ions into the soil or aquifer.<br>• The need for the use of the catalyst is dependent on the Natural Oxidant Demand value for the soil and groundwater; if the demand is high, a catalyst would not be required, thus reducing cost. | • Stage 1 Testing<br>o Low, medium, and high dose for both bromacil and tebuthiuron.<br>o Treatment reduced bromacil concentration by 70% of the initial concentration and tebuthiuron concentration by 55% of initial concentration (with addition of 40.2 g of 50% $H_2O_2$ and 4 g/kg VTX catalyst) (Bendouz and Paré, 2022).<br>o The $H_2O_2$ oxidation process using the VTX catalyst and surfactant was more expensive than the DARAMEND® technology at C$99/tonne of impacted soil (product only) for the destruction of 1.0 mg/kg contaminant concentration.<br>o Technology selected for Stage 2 testing with surfactants.<br>• Stage 2 Testing<br>o Included surfactant TWEEN (for bromacil and tebuthiuron).<br>o Treatment reduced bromacil concentration by 76% of the initial and reduced tebuthiuron concentration by 55% of initial concentration (with 40:1 oxidant to contaminant dosage and 4 g/kg VTX catalyst). |
| Surfactants | • Often used to improve contaminant availability for oxidative destruction in water phase as they help to desorb contaminants from soil components and decrease water surface tension, allowing for improved distribution of amendments in fine-grained soils.<br>• Screened based on biodegradability, availability in Alberta and approval for use in Canada:<br>o TWEEN 80; DECONIT; CHEMSOL DL3; CHEMSOL DL4; IVEYSOL 106CL; FFT. | • 3 concentrations of each surfactant were tested with bromacil and tebuthiuron.<br>• 3 of 6 surfactants were applicable for bromacil: TWEEN at 1 g/kg (74% bromacil extracted), DL3 at 5 g/kg (38%), and DL4 at 1 g/kg (28%).<br>• 3 of 6 surfactants were applicable for tebuthiuron: TWEEN at 5 g/kg (54%), DECONIT at 5 g/kg (47%), and TWEEN at 1 g/kg (31%) (Bendouz and Paré, 2022).<br>• TWEEN and DL3 react with persulfate but do not react with hydrogen peroxide, while DECONIT and DL4 are compatible with both persulfate and hydrogen peroxide. |

| Technology | Technology Summary | Bench-Scale Test Results* |
|---|---|---|
| Trap & Treat® BOS 200+® | • Trap & Treat® BOS 200+®'s treatment approach uses bio-stimulation and inoculation.<br>• Contains activated carbon, which is designed to trap the contaminants, increasing the contact time between the treatment media and the contaminants to further promote biodegradation and/or chemical reduction.<br>• Evaluated for use in permeable reactive barrier (PRB) for groundwater treatment. | • Static batch reactors filled with bromacil- and tebuthiuron-impacted soils mixed with amendment.<br>  ○ Tested with and without activated carbon component.<br>  ○ Tested with and without TWEEN 80 surfactant (and with and without activated carbon component and with ZVI).<br>• Able to destructively remove bromacil from the soil, dropping concentrations to within the target (0.009 mg bromacil/kg soil) within the four-month testing period.<br>• If treatment is required in the form of a PRB, immobilization via activated carbon and no surfactant is beneficial. Under these requirements, Trap & Treat® BOS 200+® was the best performing treatment.<br>• Successful at destructively removing tebuthiuron from the soil at a rate fast enough to reach the target (0.009 mg tebuthiuron/kg soil) within the 4-month testing period (French et al., 2023).<br>• Likely a good option for treating bromacil- and tebuthiuron-impacted sites; further testing required. |
| Trap & Treat® CAT 100 | • Trap & Treat® CAT 100's treatment approach uses chemical reduction, bio-stimulation and inoculation.<br>• Contains activated carbon, which is designed to trap the contaminants, increasing the contact time between the treatment media and the contaminants to further promote biodegradation and/or chemical reduction. | • Static batch reactors filled with bromacil- and tebuthiuron-impacted soils mixed with amendment.<br>  ○ Tested with and without activated carbon component.<br>  ○ Tested with and without TWEEN 80 surfactant (and with and without activated carbon component and with ZVI).<br>• Able to destructively remove bromacil from the soil, dropping concentrations to within the target (0.009 mg bromacil/kg soil) within the four-month testing period (French et al., 2023).<br>• The reactor with surfactant added to the simulated Trap & Treat® CAT 100 had the fastest degradation rate for bromacil.<br>• Not successful at destructively removing tebuthiuron from the soil at a rate fast enough to reach the target (0.009 mg tebuthiuron/kg soil) within the 4-month testing period. |
| Micro-scale zero valent iron (ZVI) | • ZVI's treatment approach uses chemical reduction alone. | • Static batch reactors filled with bromacil- and tebuthiuron-impacted soils mixed with amendment.<br>  ○ Tested with and without aluminum sulphate as a pH control.<br>• Able to destructively remove bromacil from the soil, dropping concentrations to within the target (0.009 mg bromacil/kg soil) within the four-month testing period (French et al., 2023).<br>• Not successful at destructively removing tebuthiuron from the soil at a rate fast enough to reach the target (0.009 mg tebuthiuron/kg soil) within the 4-month testing period. |

| Technology | Technology Summary | Bench-Scale Test Results* |
|---|---|---|
| Electrocoagulation | • Bromacil- and tebuthiuron-spiked water samples were added to an electrocoagulation cell with either Al or Fe electrodes and were subjected to various combinations of voltage and voltage application (time) cycles. | • The removal efficiency by the electrocoagulation process for bromacil ranged from 0% to 23.40%, while for tebuthiuron it was from 0 to 16% (Saint-Fort and Levy, 2022).<br>• Removal of the sterilants was generally higher with the Fe electrodes with the highest value being 23.40% while for the Al electrodes the maximum value was 16%.<br>• The low removal levels could be attributed to a lack of significant oxidative destruction and chemical transformation mechanisms under the applied electrocoagulation treatments. It also appears that there was no significant formation of stable complexation mechanism that could have led to the removal of bromacil and tebuthiuron.<br>• Further testing recommended. |

* For experiments conducted by Bendouz and Paré (2022) initial bromacil and tebuthiuron concentrations were 1.36 mg/kg and 2.1 mg/kg, respectively; for experiments conducted by French et al. (2023) initial bromacil and tebuthiuron concentrations were 0.26 mg/kg and 0.79 mg/kg, respectively; for experiments conducted by Saint-Fort and Levy (2022) initial bromacil and tebuthiuron concentrations were 4 mg/L (simulated water).

Table 18 provides a summary of the technologies that successfully reduced (or were assumed to reduce) bromacil and tebuthiuron concentrations. Based on lab, bench-scale testing, economic analysis, and technology availability, it was recommended that ISCR technology (DARAMEND®) is suitable for treatment of surface soils (<0.5 mbgs) impacted by bromacil. Further testing is required to ensure no other challenges are created through technology application that may influence site closure. Additional testing was also recommended for ISCO ($H_2O_2$ with VTX catalyst and without surfactant) technology for groundwater and saturated soil impacted by either bromacil or tebuthiuron (Bendouz and Paré, 2022) and activated carbon (AC) (Thacker, 2022). For groundwater contamination, the fact that the targeted compound is already in the water phase would facilitate its destruction via oxidative pathways. The remediation of the sorbed soil contamination would however be influenced by the sorption/desorption mechanism to make the sterilant available in the water phase. If selecting an ISCO remediation technology, it is recommended to conduct laboratory or pilot scale treatment tests to validate the amount of oxidant required to achieve the desired level of decontamination.

Table 18. Summary of technologies that showed promising results for immobilization and/or reduction of bromacil and/or tebuthiuron at the bench scale.

| High Priority Risk Management and/or Remediation Challenges | Bromacil | Tebuthiuron |
|---|---|---|
| Sterilant impacts in soil < 0.5 mbgs | • Activated Carbon (in-situ)<br>• DARAMEND® (ISCR)<br>• Trap & Treat® BOS 200+® (ISCO)<br>• Trap & Treat® CAT 100 (ISCO) | • Activated Carbon (in-situ)<br>• $H_2O_2$ with VTX catalyst (ISCO)<br>• Trap & Treat® BOS 200+® (without surfactant) (ISCO) |
| Sterilant impacts in unsaturated soil > 0.5 mbgs | • Activated Carbon (ex-situ)<br>• Trap & Treat® BOS 200+® (ISCO)<br>• Trap & Treat® CAT 100 (ISCO) | • Activated Carbon (ex-situ)<br>• Trap & Treat® BOS 200+® (without surfactant) (ISCO) |
| Sterilant impacts in saturated soil > 0.5 mbgs and groundwater | • Trap & Treat® CAT 100 (without activated carbon and with surfactant) – unconfirmed | • Trap & Treat® BOS 200+® (without surfactant) (ISCO) – unconfirmed |

* All technologies require further evaluation in the field to confirm efficacy and potential side-effects.

Three commercially available remediation technologies were recommended for meso-scale demonstration: (1) ISCO with $H_2O_2$, catalyst (VTX®) and surfactant (Tween®80); (2) immobilization with AC (Chemcarb PAC 800 powdered AC); and (3) ISCR with DARAMEND®.

### 4.5 Meso-scale Ex-situ Remediation Technology Field Trial

A 12-week, outdoor meso-scale experiment focused on bromacil degradation and immobilization in soil was conducted in 2022 to evaluate the effectiveness of three technologies for remediating bromacil-impacted soil sourced from a former substation near Trochu, Alberta (Bachmann and Thiessen, 2023). No sites were available as a source of tebuthiuron-impacted soil, therefore the meso-scale experiment only focused on bromacil. Approximately 90 $m^3$ of silty clay soil impacted by bromacil ranging from 0.24 to 1.76 mg/kg, was hauled to a lined treatment cell in Vegreville, Alberta, homogenized and divided into 12 unique, 3.0 x 3.0 x 0.6 m (5.4 $m^3$) cells. Experimental design consisted of three replicates of three treatments (1 application rate/ treatment) and three control replicates randomized on the treatment cell (Figure 10). Each cell was isolated and covered with a polyethylene multipurpose liner to prevent interference between treatments and maintain a consistent soil moisture content throughout the experiment. Table 19 provides a summary of the meso-scale remediation trial and the associated results from the experiment.

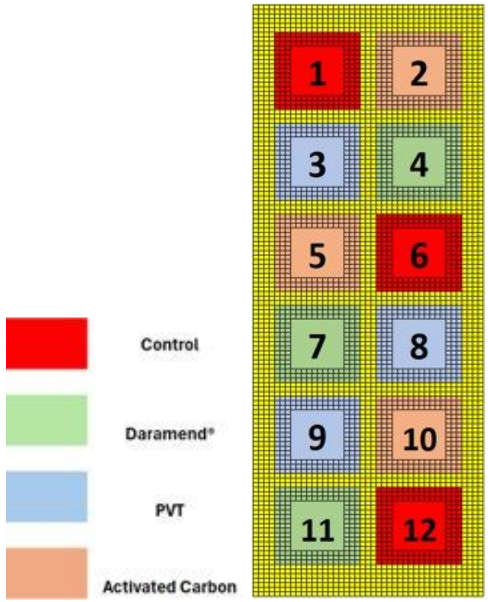



Figure 10. Meso-scale field experiment design evaluating immobilization and destructive remediation technologies.

Table 19. Experimental results from a meso-scale ex-situ remediation trial evaluating immobilization and destructive remediation technologies.
From Bachmann and Thiessen (2023).

| Experimental Treatment | Results |
|---|---|
| Immobilization technology – AC (Chemcarb PAC 800 powdered AC) (Replicate #'s 2, 5 and 10 in Figure 10)<br>• 75 kg powdered product applied in slurry form.<br>• Mixed with water in a blending container prior to application to soil.<br>• Targeted moisture content >80% of soil water holding capacity. | • Statistically significant decrease in total bromacil concentrations (73 ± 6% reduction from 0.50 ± 0.2 mg/kg to 0.13 ± 0.07 mg/kg total bromacil concentration (i.e., total)) over 12 weeks.<br>• Phyto-accessible bromacil concentrations reduced from 0.06 mg/kg (which was 8% of initial bromacil concentration measured by solvent extraction) to <0.008 mg/kg (the laboratory detection limit) within 2 weeks. |
| In-situ Chemical Oxidation ($H_2O_2$, catalyst (VTX®) and surfactant (Tween®80)) Replicate #'s 3, 8 and 9 in Figure 10)<br>• 250 kg 50% $H_2O_2$, 30 kg 22% VTX® catalyst, and 10 kg Tween®80 surfactant.<br>• Reagents mixed in a blending container with water prior to application to soil. | • ISCO technology was handled and applied incorrectly – catalyst, surfactant and $H_2O_2$ were mixed in a blending container prior to application to soil resulting in the desired reaction occurring before being applied to the sterilant impacted soil.<br>• As a result, the treatment was not effective at reducing bromacil concentrations in impacted soil.<br>• Recommended for further testing with tebuthiuron-impacted soils as halogenated contaminants such as bromacil generally require reductive mechanisms for efficient contaminant degradation or transformation. |

| Experimental Treatment | Results |
|---|---|
| In-situ Chemical Reduction (DARAMEND®) Replicate #'s 4, 7 and 11 in Figure 10)<br>• 265 kg DARAMEND® powder applied in slurry form.<br>• Mixed with in a blending container prior to application to soil.<br>• Targeted moisture content >80% of soil water holding capacity. | • 57 ± 1% decrease in total (i.e., total) bromacil concentrations (0.56 ± 0.09 mg/kg to 0.24 ± 0.01 mg/kg).<br>• Multiple applications may be required to achieve Tier 1 Soil Guideline (0.009 mg/kg) concentrations. |

Further testing was recommended for optimization of ISCR technology (DARAMEND®) application rates and moisture conditions. ISCO technologies should be re-evaluated and tested for treatment of groundwater impacted by sterilants. Important learnings from executing the meso-scale field trial for practical application of either immobilization or reductive remediation technologies include (Bachmann and Thiessen, 2023):

- Powdered adsorbent or ISCR technologies require mixing with water in a blending container prior to application to impacted soil. For field-scale application, this may require a caisson drill or other similar mixing equipment. Specialized PPE may be required when handling the AC or ISCR technologies.
- The slurry required to optimize in-situ contact between the treatment technology and impacted soil at field-scale applications will result in additional water access, earth moving, and geotechnical considerations.
- The source of activated carbon should be considered to avoid the release of unintended contaminants (e.g., heavy metals) to the environment (e.g., walnut shells vs. coal-based activated carbon).

### 4.6 Optimization Meso-scale Field Trial

A one-year field optimization trial was established at the InnoTech Alberta mesocosm facility in Vegreville to evaluate DARAMEND® dosage rate, application frequency, and moisture content on bromacil-impacted soil in a mesocosm setting (Table 20; Bachmann, 2024). A lab study was also performed to assess the use of bench-scale scale studies for Daramend® optimization for field planning.

Table 20. Experimental design for the field study.

| Parameter | Quantity | Description |
|---|---|---|
| Soil | 1 | Bromacil-impacted soil from Bow Island, AB. |
| Daramend® | 3 | Control (0%), 0.5%, 2.0% by dry soil weight |
| Moisture Regime | 2 | Moisture Regime 1: Initial moistening only, initial moistening and moistening 30 days after amendment |
| | | Moisture Regime 2: Initial moistening and moistening 28 days after amendment.<br>Additional Daramend® and water application 44 weeks after initial amendment (field study only). |
| Replicates | 4 | 4 $m^3$ treatment cells or 4 L jars |
| Total | 24 | Total number of treatment cells |

None of the treatments in the mesoscale study were able to reach the Alberta Tier 1 target of 0.009 mg/kg (Figure 11). The bromacil concentration for all treatments in the lab study decreased to within 0.003 mg/kg of the minimum detection limit (0.008 mg/kg) and treatments were not significantly different from each other.

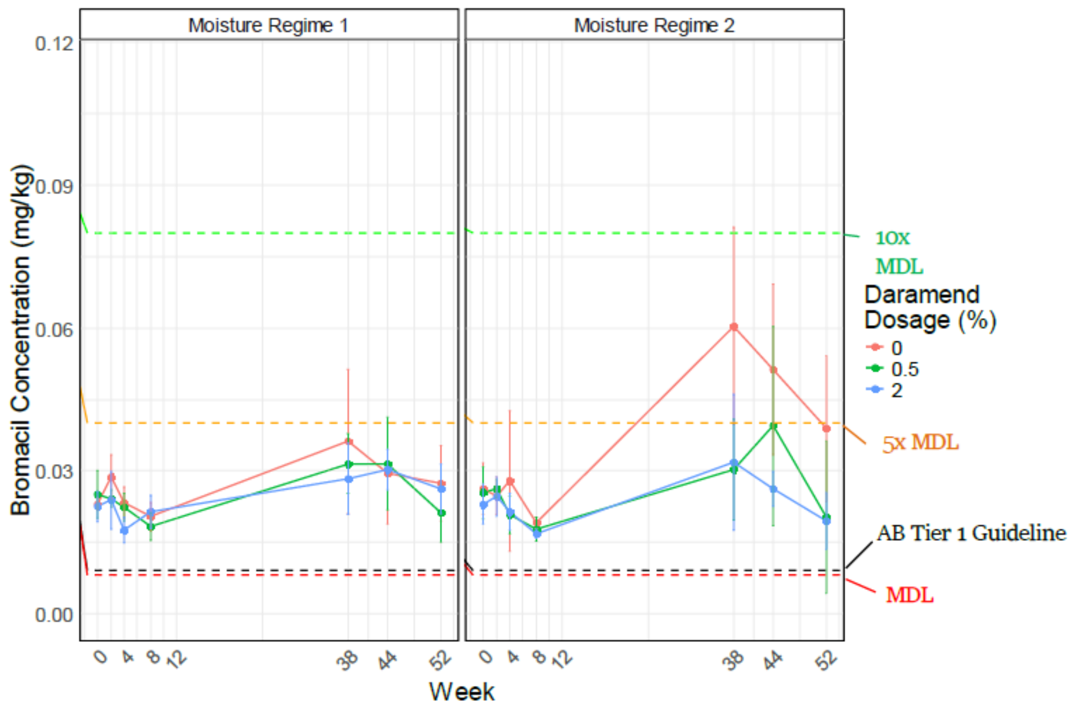



Figure 11. Average bromacil concentration for each treatment.

Bromide concentrations increased for all field Daramend® treatments in Moisture Regime 2, and 2% Daramend® treatments in Moisture Regime 1, indicating that bromacil was being destructively remediated in those treatments. In the lab study, Daramend® treatments had higher bromide concentrations than controls.

For this soil, it appears that the limiting factor for bromacil degradation was moisture content and Daramend® was able to enhance degradation. The addition of water seems to release more bromacil from the soil phase and the application of Daramend® buffers this release by degrading the released bromacil. Bromacil is degraded via reductive debromination, an anaerobic process. Achieving and maintaining the required moisture content on fine-textured surface soil in in-situ applications of Daramend® is logistically unfeasible. Daramend® and other anaerobic technologies maybe better suited for application in ex-situ reactors where the prolonged saturation of the impacted soil can be achieved and maintained.

### 4.7 Knowledge Gaps and Recommended Practices

Fate and behavior of soil sterilants in the environment is complex and influenced by multiple environmental and chemical-specific factors. Four priority remediation challenges were identified for potential solutioning through the SSP: (1) sterilants within surface soil (≤ 0.5 mbgs); (2) sterilants at depths greater >0.5 mbgs in unsaturated soil; (3) saturated fine-grained till soils and groundwater impacted by sterilants and (4) groundwater impacted by sterilants. Several knowledge gaps remain associated with remediation technologies applicable to bromacil- and tebuthiuron-impacted soil and groundwater including:

In-situ Remediation Technologies

- The effectiveness of new and novel in-situ destructive remediation technologies such as electrocoagulation.
- Best practices for the use of AC as an immobilization technique, including factors such as:
    - Type of AC (feedstock and charring temperature)
    - Methods of incorporation into soil (including moisture content)
    - The influence of AC on the extraction and analysis of total bromacil and tebuthiuron concentrations using the accelerated solvent extraction method (ASE) investigated in the SSP.
- In-situ remediation of saturated fine-grained till soils and groundwater impacted by sterilants.
- Remediation of groundwater impacted by sterilants.
- The suitability for treating bromacil and tebuthiuron alone and in combination using Trap & Treat® BOS 200+®, particularly for application in a permeable reactive barrier to prevent off-site migration.

Ex-situ Remediation Technologies

- The potential for concurrent or sequential application of different treatment technologies and risk assessment methods for achieving closure.
- Practical methods for maintaining reductive soil conditions (i.e., moisture conditions) to enable ISCR technology (DARAMEND®) to work effectively.
- The effectiveness of new and novel ex-situ destructive remediation technologies.
- Updated cost and greenhouse gas emission analysis for ex-situ technologies including thermal desorption, ISCR technology (DARAMEND®) and landfilling.

A summary of recommended practices and opportunities for improved management practices associated with remediation of bromacil and tebuthiuron impacted sites is provided in Table 21.

Table 21. Recommended practices associated with high priority remediation challenges for bromacil- and tebuthiuron-impacted sites.

<table>
<tr><th rowspan="2">High Priority Remediation Challenges</th><th colspan="2">Recommended Practices</th></tr>
<tr><th>Bromacil</th><th>Tebuthiuron</th></tr>
<tr><td rowspan="2">Sterilants within surface soil (≤ 0.5 mbgs)</td><td colspan="2">• Conduct bench-scale tests with impacted soil to assess treatment application rates based on soil properties and Phase 2 ESA data for sterilant concentrations.<br>• Destructive and immobilization technologies must be applied in slurry form to optimize in-situ soil contact (recommended moisture content – 80% of soil water holding capacity).<br>• Apply immobilization technologies (i.e., AC) in-situ.<br>• For destructive remediation technologies excavate impacted soil for treatment in a constructed treatment cell (on- or off-site).<br>  o Construct treatment cell to enable impacted soil depth within the cell to be ≥0.6 m.</td></tr>
<tr><td>• ISCR technology DARAMEND®<br>  o Monitor soil moisture during treatment to maintain moisture conditions and reducing soil environment.<br>• AC<br>• Thermal desorption.</td><td>• ISCO $H_2O_2$ with catalyst and surfactant (requires further investigation).<br>• AC<br>• Thermal desorption.</td></tr>
<tr><td>Sterilants at depths greater >0.5 mbgs in unsaturated soil</td><td colspan="2">• Excavate un-impacted soil to expose impacted zone and store on-site for reclamation.<br>• Excavate impacted soil and treat in a constructed treatment cell (on- or off-site) in the same manner as described above, or with previously proven technologies such as thermal desorption.</td></tr>
<tr><td>Saturated fine-grained till soils and groundwater impacted by sterilants</td><td colspan="2">• Ex-situ – technologies and recommended practices described above apply.</td></tr>
<tr><td>Groundwater impacted by sterilants</td><td colspan="2">• Applicable technologies for groundwater treatment described in Levy et al. (2021).</td></tr>
</table>

ISCR – In-Situ Chemical Reduction; ISCO – In-Situ Chemical Oxidation; AC – Activated Carbon

## 5.0 SSP OUTCOMES

The SSP goal was to develop proven, technical, and cost-effective strategies and best practices for management of sites impacted by residual soil sterilants, with the goal of achieving regulatory site closure through remediation or acceptable risk assessment strategies.

The program was structured following the basic steps in a remediation program: (1) Identification and Delineation, (2) Risk Assessment, and (3) Remediation. For each of these steps, a list of Problem Statements was developed to guide a suite of research projects to address knowledge gaps. Table 22 lists the SSP outcomes for each of these Problem Statements. Another goal of the SSP was to share knowledge with program participants and a broader base of practitioners; outcomes of knowledge transfer activities are also provided in Table 22.

Effective management of sterilant-impacted sites has many interdependencies between identification and delineation of the contaminants and the best risk management and/or remediation approach to closure. The SSP projects were intended to break new ground in the management of sterilant-affected soil and water. As such, many of the findings need to be validated through evaluation of sites from a variety of Alberta conditions to confirm broad applicability. Among others, conditions such as sterilant levels, co-contaminants, site age (sterilant weathering), site soil and/or groundwater characteristics, and climate considerations need to be evaluated.

A key consideration for all scenarios identified is whether the primary goal is to address high concentrations to reduce risk, or lower concentrations to meet remediation endpoints. Technologies and management strategies should be selected according to the end goal. Given the heterogeneous distribution of sterilants and unique conditions at most sites, a variety of approaches may be required at each site.

Table 22. SSP outcomes achieved for each knowledge gap.

| SSP Program Component | SSP Knowledge Gap | SSP Outcome |
|---|---|---|
| Identification and Delineation | Practitioners are uncertain about when and where to screen for soil sterilants, leading to unnecessary intrusive sampling following Phase I environmental sites assessments, excessive analysis with associated costs, and identification of sterilants late in the assessment process that cause reclamation delays. | • Detailed sampling protocols for soil and water were developed that will reduce the potential for cross-contamination and sample dilution.<br>• Potential technologies for field-screening soil and water to provide for more efficient sampling were revied and two potential technologies were identified as promising. |
| | Analytical methods currently used in Alberta to characterize sterilants found in soil and/or water have variable detection limits, sometimes higher than guideline levels, and only provide total, rather than plant-accessible, concentrations. | • A new laboratory analytical procedure was developed that provides significantly more precise measures of bromacil and tebuthiuron in soil and water samples with minimum detection limits that are below Tier 1 Guidelines values.<br>• A sample extraction procedure was developed to analyze phyto-accessible levels of sterilants in soils which will more realistically represent the amount of sterilant in a sample that will affect vegetation. |

| SSP Program Component | SSP Knowledge Gap | SSP Outcome |
|---|---|---|
| Risk Assessment | Accurate Alberta-specific chemical data for bromacil and tebuthiuron for use in risk assessment models (e.g., half-life, Koc, Kd) are not available. | • A laboratory study established adsorption coefficient (Kd and Koc) values for bromacil and tebuthiuron in Alberta soils with varying organic matter contents and textures. |
| | Alberta Tier 1 regulatory guidelines are limited by the ecological contact pathways for the protection of irrigation water and freshwater aquatic life. | • Thirty risk assessment models were reviewed and ranked based on their defensibility, applicability, availability, ease of use, and inclusion of novel features relative to the current Tier 2 model.<br>• Three models were subjected to a detailed mechanistic review and model analysis based on standard Tier 1 input values and parameters derived from the literature when necessary.<br>• None of the models reviewed could effectively replace all elements of the Tier 2 model however they could be useful supplements. |
| | Sterilant toxicity data for Alberta native plant species is incomplete or missing. | • Toxicity of sterilants to six native grass species was shown to be greater than the agricultural crops used in the Tier 1 Guidelines – revised guidelines based on these data were more stringent than the current Tier 1 guidelines for ecological direct contact surface soil quality for fine-grained soil. |
| Remediation | Long-term evaluations of remediation treatment longevity, which is particularly relevant for immobilization treatments that rely on sterilant adsorption such as activated carbon, are not available. | • Activated Carbon was shown to effectively sorb the majority of bromacil and tebuthiuron in the long-term which should lead to greater acceptance by practitioners and regulators of this remediation technology. |
| | Detailed, publicly accessible data on operational-scale treatment demonstrations in Alberta (e.g., target sterilant(s) and concentrations, co-contaminants, methods, rates, and costs) are not available. | • This was confirmed as an ongoing need through a literature review and discussions with practitioners. |
| | Information on the potential for, and value of, combining treatment technologies to increase remediation success is lacking. | • Several lab- and field-scale trials were conducted using various treatment technologies with and without catalysts and surfactants. Results varied by sterilant. |

| SSP Program Component | SSP Knowledge Gap | SSP Outcome |
|---|---|---|
| | Other remediation outcomes – *Inventory and ranking of remediation technologies* | • A catalogue and ranking of existing remediation technologies was developed to assist practitioners in screening potential technologies for use at their site.<br>• Three promising remediation technologies (DARAMEND®, Electrocoagulation, and Trap & Treat® and Zero Valent Iron) were tested at the bench-scale.<br>o DARAMEND® was found to be suitable for use in treatment of bromacil in soil and water but is not able to treat tebuthiuron.<br>o Trap & Treat® BOS 200+® was successful in adsorbing and degrading both bromacil and tebuthiuron.<br>o Electrocoagulation removed limited amounts of sterilants in soil and requires further development if it is to be considered for field deployment. |
| | Other remediation outcomes – *Meso-scale evaluation of three remediation technologies* | • A mesoscale experiment tested three commercially available remediation technologies: (1) chemical oxidation with a surfactant via PeroxyChem 50% hydrogen peroxide, VTX®, and Tween®-80 (the oxidant); (2) adsorption with Chemcarb PAC 800 powdered activated carbon (the adsorbent); and (3) biological and chemical reduction with DARAMEND® (the reductant) of bromacil degradation and immobilization in soil:<br>o Total bromacil concentrations were reduced, however they remained an order of magnitude greater than the Tier 1 Guideline suggesting these technologies may be appropriate for contaminated sites where a less stringent Tier 2 soil remediation guideline is applicable or where a risk management plan is implemented.<br>o Phyto-accessible bromacil in the activated carbon-treated soil decreased to below the Tier 1 Guideline which supports the use of the tested adsorbent as a risk management tool at bromacil-impacted sites.<br>• An optimization trial of DARAMEND® resulted in none of the treatments in the mesoscale study reaching the Alberta Tier 1 target of 0.009 mg/kg, though increased bromide levels indicated bromacil destruction was occurring. |
| Knowledge Transfer | A community of practice consisting of practitioners, industry, and government representatives is developed and retained. | • Approximately 45 people joined the Community of Practice and participated in the Annual Sharing Events. |
| | Technical information is disseminated through annual workshops and external presentations. | • Four Annual Sharing Events were held, with presentations on the overall program, and on each of the active projects.<br>• 13 external presentations were given in a variety of forums by the Program Manager and individual researchers. |

## 6.0 REFERENCES


AEP (Alberta Environment and Parks), 2016a. Alberta Environmental Site Assessment Standard. March 1, 2016.

AEP (Alberta Environment and Parks), 2016b. Alberta Exposure Control Guide. May 3, 2016.

AEP (Alberta Environment and Parks), 2017. Alberta Risk Management Plan Guide. Alberta Environment and Parks, Edmonton, Alberta. AEP Land Policy 2017 No. 2. 58 pp. https://open.alberta.ca/publications/9781460136102

AEP (Alberta Environment and Parks), 2022a. Alberta Tier 1 Soil and Groundwater Remediation Guidelines. Land Policy Branch, Policy and Planning Division. 189 pp.

AEP (Alberta Environment and Parks), 2022b. Alberta Tier 2 Soil and Groundwater Remediation Guidelines. Land Policy Branch, Policy and Planning Division. 129 pp.

AESRD (Alberta Environment and Sustainable Resource Development), 2014. Contaminated Sites Policy Framework. Land and Forestry Policy Branch, Policy Division. 25pp.

Bachmann, V. and M. Tindal, 2023. Determination of Soil-Water and Organic Carbon-Water Partitioning Coefficients for Bromacil and Tebuthiuron. Report SSP-7C Prepared by InnoTech Alberta and Millennium EMS Solutions Ltd. for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 15 pp.

Bachmann, V., 2024. Optimization of Daramend® for the Remediation of Bromacil in Soil. Report SSP-12B prepared by InnoTech Alberta for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 27 pp.

Bendouz, M. and J. Paré, 2022. Bench-scale Test of DARAMEND® to Remediate Bromacil and Tebuthiuron in Soil. Report SSP-11A prepared by Chemco Inc. for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 45 pp.

Domenico, P.A. and G.A. Robbins, 1985. A New Method of Containment Plume Analysis. Ground Water 23: 476-485.

Domenico, P.A., 1987. An Analytical Model for Multidimensional Transport of Decaying Contaminant Species. Journal of Hydrology 91: 49-58.

Drozdowski, B., C.B. Powter and S. Levy, 2018a. Management of Sterilant Impacted Lands: Literature Synthesis. InnoTech Alberta, Edmonton, Alberta. 49 pp. https://www.cclmportal.ca/resource/management-sterilant-impacted-sites-literature-synthesis

Drozdowski, B., S. Levy and C.B. Powter, 2018b. Remediating Soil Sterilant-Affected Lands: Summary of Stakeholder Discussions. InnoTech Alberta, Edmonton, Alberta. 42 pp. https://www.cclmportal.ca/resource/remediating-soil-sterilant-affected-lands-summary-stakeholder-discussions

French, K., E. Cowan and A. Neufeld, 2021. Preliminary Testing of Existing Field Screening Technologies for Bromacil and Tebuthiuron – Phase 1 Results. Report SSP-5B prepared by Vertex Environmental Inc. for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 28 pp. pus Appendices.

French, K., E. Cowan and A. Neufeld, 2023. Bench Scale Treatability Study using Trap & Treat® and Zero Valent Iron for Bromacil and Tebuthiuron in Alberta Soils. Report SSP-11C prepared by Vertex

Environmental Inc. for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 20 pp. plus lab data.

French, K., E. Cowan, E. Terpstra, J. Liu, Y. Li and F. He, 2021. Field Screening Technologies for Bromacil and Tebuthiuron – Literature Review. Report SSP-5A prepared by Vertex Environmental Inc. and University of Waterloo for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 28 pp. plus Appendices.

Government of Alberta, 2000. Environmental Protection and Enhancement Act. Revised Statutes of Alberta 2000. Chapter E-12. https://kings-printer.alberta.ca/1266.cfm?page=E12.cfm&leg_type=Acts&isbncln=9780779785285

Hemsley, T., K. Bessie and A. Shaikh, 2021. Sterilant Sampling Best Management Practices. Report SSP-2 prepared by Tetra Tech Canada Inc. for Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 41 pp.

Houston, A., T. Todoruk, B. Loescher and R. Prosser, 2020. Laboratory Experimental Design to Characterize Bromacil and Tebuthiuron Half-life and Adsorption in Alberta Soils. Report SSP-6/8B prepared by Advisian, Bureau Veritas Labs and University of Guelph for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 64 pp.

Levy S., X. Mo and V. Bachman, 2021. Evaluation and Comparison of Remediation Technologies. Report SSP-13 prepared by InnoTech Alberta for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 30 pp.

Litalien, A., J. Hueser, M. Tindal, C. Kartz and I. Mitchell, 2020. Risk Assessment for Protection of Irrigation Water and Freshwater Aquatic Life: Review of Alternative Models. Report SSP-7B prepared by Millennium EMS Solutions Ltd. for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 26 pp. plus Appendices.

Litalien, A., C. Kartz and I. Mitchell, 2020. Review of Bromacil and Tebuthiuron Data in Support of Irrigation Water and Freshwater Aquatic Life Guidelines. Report SSP-7A prepared by Millennium EMS Solutions Ltd. for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 54 pp.

Litalien, A. and M. Tindal, 2021. Ecological Contact Guideline Development for Bromacil and Tebuthiuron. Report SSP-9B prepared by Millennium EMS Solutions Ltd. for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 16 pp. plus Appendices

Marquez, G., A. Houston and T. Todoruk, 2020a. Literature Review to Identify Metabolites of Bromacil and Tebuthiuron. Report SSP-6/8C prepared by Advisian, Worley Group for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 18 pp.

Marquez, G., A. Houston and T. Todoruk, 2020. Sensitivity Analysis of the Domenico and Robbins Groundwater Transport Model. Report SSP-6/8A prepared by Advisian for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 21 pp. plus Appendices.

Maxwell, J.L., 2022. Development of an Extraction Method for Estimating Phyto-accessible Fractions of Bromacil and Tebuthiuron. M.Sc. Thesis. Department of Renewable Resources, University of Alberta, Edmonton, Alberta. 51 pp. https://doi.org/10.7939/r3-c6w5-nk49

Pereira, A.D.S., E.D. Ruan and G. Knox, 2022. Laboratory Method Investigation for Detection of Bromacil and Tebuthiuron in Water and Soil. Report SSP-3 prepared by InnoTech Alberta for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 38 pp.

Powter, C.B. and B. Drozdowski, 2024. Soil Sterilants Program: Project Report Compilation and Summary. Report SSP-14A prepared by InnoTech Alberta and Enviro Q&A Services for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 47 pp. plus appendices.

Saint-Fort, R. and S. Levy, 2022. Proof of Concept of Electrocoagulation Technology to Remediate Water Contaminated with Bromacil and Tebuthiuron. Report SSP-11B prepared by Mount Royal University and InnoTech Alberta for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 7 pp. plus appendix.

Stantec Consulting Ltd., 2008. Ecotoxicity Evaluation in Support of the Derivation of Tier 2 Values for Tebuthiuron. Report prepared for EBA Engineering Consultants Limited. File No. 160960313. 93 pp.

Stantec Consulting Ltd., 2012. Ecotoxicity Assessment of a Soil Sterilant – Bromacil. Report prepared for Cenovus Energy Inc. c/o Kathryn Bessie, EBA Engineering Consultants Limited. File No. 122160059. 277 pp.

Thacker, S., 2021. Toxicity of Bromacil and Tebuthiuron to Alberta Native Plant Species. Report SSP-9 prepared by InnoTech Alberta for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 54 pp.

Thacker, S., 2022. Investigation of Long-Term Effects of Activated Carbon in Immobilization of Bromacil and Tebuthiuron. Report SSP-10 prepared by InnoTech Alberta for Soil Sterilants Program, InnoTech Alberta, Edmonton, Alberta. 55 pp.

## APPENDIX A: Bromacil and Tebuthiuron Physical and Chemical Characteristics

Common physical and chemical characteristics of bromacil and tebuthiuron.

| Soil Sterilant | Relevant Physical and Chemical Characteristics |
| --- | --- |
| **Bromacil**<br>Chemical name: 5-bromo-3- (butan-2-yl)-6-methylpyrimidine-2,4(1H,3H)- dione<br>Substituted uracil herbicide<br>Commonly used product names: bromacil, 317-40-9; Bromazil, Uragan, Hyvar X (spray), Calmix (combined with 2,4-D as pellets), Krovar (combined with diuron)<br>Typically available in the form of a wettable powder or a liquid | Appearance: Colourless to white crystalline solid<br>Available as wettable powder, soluble concentrate or granular<br>Molecular Formula: $C_9H_{13}BrN_2O_2$<br>Molecular weight: 261.119 g/mol<br>Melting point: 158-160°C<br>Solubility in water: 815 mg/L @25°C<br>Vapour pressure: negligible @25°C |
| **Tebuthiuron**<br>Chemical name: 1-(5-tert- Butyl-1,3,4-thiadiazol-2-yl)-1,3-dimethylurea<br>Commonly used product names: Spike, 34014-18-1, Graslan, Perflan, Brulan; Herbec 20P<br>Typically available in the form of granules or pellets | Appearance: Colourless crystals<br>Non corrosive<br>Molecular Formula: $C_9H_{16}N_4OS$<br>Molecular weight: 228.314 g/mol Melting point: 164°C<br>Solubility in water: 2,500 mg/L @25°C<br>Vapour pressure: 2.0 x 10-6 mm Hg @25°C |

## APPENDIX B: Bromacil and Tebuthiuron Metabolites and Degradation Processes

### Bromacil

| Chemical Name | Molecular Weight | Suspected Process/Mechanism |
|---|---|---|
| Bromacil (parent compound) | 261.12 | ___ |
| 5-bromo-3-sec-butyl-6-hydroxymethyluracil (Metabolite A) | 277.11 | Biodegradation |
| 5-bromo-3-(alpha-hydroxymethylpropyl)-6-methyluracil (Metabolite C) | 277.11 | Biodegradation |
| 5-bromo-3-(2-hydroxy-1-methylpropyl)-6-methyluracil (Metabolite D) | 277.11 | Biodegradation |
| 3-sec-butyl-6-methyluracil (Metabolite F) | 182.22 | Biodegradation, Debromination, Photodecomposition in aqueous solutions |
| 5-bromo-6-methyluracil (Metabolite G) | 205.01 | Biodegradation |
| 3-sec-butyl-5-acetyl-5-hydroxyhydantoin | 214.22 | Ozonation, Photodegradation |
| 3-sec-butyl-5,5-dibromo-6-methyl-6-hydroxyuracil | 358.03 | Ozonation, Sensitized Sunlight Photodegradation |
| 3-sec-butylparabanic acid | 170.17 | Ozonation |
| Debromobromacil Radical Dimer | 362.43 | Sensitized Sunlight Photodegradation |

### Tebuthiuron

| Chemical Name | Molecular Weight | Suspected Process/Mechanism |
|---|---|---|
| Tebuthiuron (parent compound) | 228.31 | ___ |
| N-(5-(2-hydroxy-1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl)-N,N'-dimethylurea (Metabolite 103[OH]) | 244.32 | Plant Metabolism |
| N-(5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl)-N-methylurea (Metabolite 104) | 214.29 | Biodegradation, Mammal Metabolism, Plant Metabolism |
| N-(5-(2-dimethylethyl)-1,3,4-thiadiazol-2-yl)-N-methylurea (Metabolite 104[OH]) | 230.29 | Mammal Metabolism |
| N-(5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl) urea (Metabolite 106) | 200.26 | Mammal Metabolism |
| 5-(1,1-dimethylethyl)-2-methylamino-1,3,4-thiadiazol (Metabolite 107) | 171.27 | Biodegradation |
| 2-dimethylethyl-5 amino-1,3,4-thiadiazol (Metabolite 108) | 157.24 | Biodegradation, Mammal Metabolism |
| N-(5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl)-N'-hydroxymethyl-N-methylurea (Metabolite 109) | 244.32 | Mammal Metabolism, Plant Metabolism |

| Chemical Name | Molecular Weight | Suspected Process/Mechanism |
|---|---|---|
| N-(5-(2-hydroxy-1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl)-N'-hydroxymethyl-N-methylurea (Metabolite 109[OH]) | 260.32 | Mammal Metabolism |