Evaluating Technology-Based Assessments in Wellsite Reclamation

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Report Prepared for

Petroleum Technology Alliance of Canada

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REPORT REVIEW AND APPROVAL

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EXECUTIVE SUMMARY

Under Alberta's regulatory framework, companies must obtain a reclamation certificate to demonstrate that upstream oil and gas sites have been returned to equivalent land capability and are self-sustaining. Traditionally, this assessment relies on extensive fieldwork, which is labor-intensive, costly, and introduces safety risks, particularly in remote locations. This challenge is particularly significant as Alberta's oil and gas industry works to reclaim hundreds of thousands of wellsites sites.

This project explored the use of remote sensing technologies to support the assessment of wellsite reclamation status in Alberta. The goal was to understand how these tools might complement existing in-field assessment practices, particularly under Alberta's 2010 Reclamation Criteria. The study involved assessment of reclaimed and non-reclaimed wellsites, using airborne LiDAR and optical multispectral imagery analysis combined with expert opinion and approaches from environmental consultants.

We show that remote sensing can complement in-field assessments, provide quality control, and support the monitoring of site progress over time. Our results demonstrate that remote sensing technologies can support regulatory reclamation guidelines by assessing stem counts, the distribution of woody vegetation across the wellsite, and the assessment of elevation and topographic anomalies of the soil surface. However, at the currently common spatial resolutions, remote sensing technologies are unable to clearly differentiate between desired and undesired herbaceous species, an important criteria under the 2010 Reclamation Criteria for Wellsites and Associated Facilities for Forested Lands. While professional judgment can help in such cases, for example, based on the history of the wellsite, assessing this aspect using remote sensing data alone remains challenging. Since these limitations are primarily technical rather than fundamental, we believe that advancements in remote sensing technology will address these challenges, leading to more accurate and comprehensive assessments in the future.

Key Findings

- Remote sensing can complement field assessments by contributing valuable data on vegetation structure (e.g., stem counts, canopy development), distribution of woody vegetation, and topographic features.
- Some limitations remain. Current technologies are not yet able to reliably distinguish between desirable and undesirable herbaceous species, an important requirement in vegetation assessments. This means remote sensing alone is not sufficient for complete evaluation under the 2010 Reclamation Criteria.
- Timing matters. Remote sensing is most effective when applied to sites that are 5 to 7 years post-reclamation, when vegetation, particularly woody species, has had sufficient time to

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establish. Assessing sites too early using remote sensing increases the likelihood of inaccurate results.

- Risk of misclassification:
  - False negatives may occur if early-stage woody vegetation is not detected, even when a site would pass an in-field assessment.
  - False positives may occur if undesirable species are present but not visible in remote sensing data, which could result in a reclamation certificate being issued prematurely.
- Multitemporal imagery acquisition is critical. Well-timed seasonal imagery, particularly across multiple years, improves the reliability of remote sensing assessments by capturing vegetation variability over time.

Considerations for Practice

- Integration is key. The current strength of remote sensing lies in supporting, not replacing, in-field assessments. When used together, the two approaches can improve confidence in site evaluations, particularly where field access is limited or where historical site data exists.
- Drone technologies have the potential to collect data with higher resolution, particularly useful for identifying small woody vegetation. However, operational constraints under current regulations (e.g., line-of-sight limits) limit their widespread application. Proposed updates to allow BVLOS (Beyond Visual Line-of-Sight) drone flights may enhance future capabilities.
- Transparency in methods is essential. Regulators and auditors require clear, well-documented remote sensing methodologies, including metadata, processing steps, and justification for interpretation. This improves understanding and acceptance of remote assessments.
- Site history and context remain essential to interpreting remote sensing results, especially when image resolution or data availability is limited. Professional judgment and site-specific knowledge continue to play a critical role.

Applications and Recommendations

- Triage and pre-screening: Remote sensing can help classify sites into “pass,” “uncertain,” and “fail” categories, helping prioritize in-field efforts where they are most needed.
- Standardization and benchmarking: Developing and sharing field-validated remote sensing datasets can support consistency and allow comparison across consultants. The Open Data Areas Alberta Project may serve as a foundation for such a reference library.
- Landscape type affects data needs. In forested settings, LiDAR is particularly useful for evaluating structural vegetation indicators. In grasslands or cultivated lands, moderate-resolution imagery from satellites may be sufficient for monitoring vegetation cover and productivity trends.

Conclusion

Remote sensing technologies offer valuable support to reclamation assessment efforts, particularly for older or remote wellsites. While current tools are not a substitute for in-field assessments, their strategic use can improve the efficiency, consistency, and transparency of certification processes. As data quality and accessibility continue to improve, combining remote sensing with on-the-ground evaluations will be key to managing Alberta's large inventory of abandoned wellsites and ensuring responsible reclamation outcomes. Remote sensing approaches should be re-evaluated for their ability to reliably replace in-field assessments, as improvements in spatial and temporal resolution will reduce the risk of misclassification over time.

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BEST PRACTICES /EMISSIONS REDUCTIONS/TANGIBLE PROJECT OUTCOMES

Best Practices

This project demonstrated that remote sensing technologies can complement, but not replace, in-field assessments of reclaimed and non-reclaimed wellsites at this time. When used strategically, they can support more efficient, transparent, and scalable reclamation evaluations.

Remote sensing is most reliable on sites that are at least five to seven years post-reclamation, when vegetation structure, particularly woody species, is more easily detectable. While LiDAR and multispectral imagery can capture broad indicators such as topographic anomalies, canopy development, and overall site progression, they cannot reliably differentiate desirable from undesirable herbaceous species. This remains a critical limitation, reinforcing the need for field validation.

Full documentation of data sources, processing steps, and assumptions are essential for building regulator confidence and supporting consistent interpretation across projects.

Emissions Reductions

While not the primary focus, remote sensing approaches contribute to emissions reductions by decreasing the need for field travel, particularly in remote or hard-to-access areas. When used to pre-screen sites into categories such as "pass," "uncertain," and "fail," remote assessments can reduce the number of field visits to sites by limiting in-field assessments to timing where a pass is likely, leading to reductions in travel-related emissions for sites on average.

Future drone-based monitoring, particularly under proposed Beyond Visual Line-of-Sight (BVLOS) regulations, may further reduce travel demands. By enabling wide-area surveys without repeated site visits, these advancements offer promising emissions and cost efficiencies.

Tangible Project Outcomes

This project produced several practical outcomes for industry and regulators. It confirmed the value of remote sensing in evaluating vegetation structure and site conditions over time, while clearly identifying current technological limitations.

The work also underscored the importance of transparency and consistency in remote sensing workflows, and highlighted the potential for building standardized, field-validated datasets to support future assessments. While current remote sensing tools are best suited to support rather than replace fieldwork, combining these methods offers a viable path toward more efficient, scalable, and cost-effective reclamation practices.

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LIST OF ACRONYMS

ABMI	Alberta Biodiversity Monitoring Institute
AEPA	Alberta Environment and Protected Areas
AER	Alberta Energy Regulator
Al-Pac	Alberta Pacific Forest Industries
avg	Average
BVLOS	Beyond Visual Line-of-Sight
CNRL	Canadian Natural Resources Limited
CPH	Canopy Height Model
DEM	Digital Elevation Model
DEP	Derived Ecosite Phase
DSA	Detailed Site Assessment
DSM	Digital Surface Model
EVI2	Two-Band Enhanced Vegetation Index
GNDVI	Green Normalized Difference Vegetation Index
ISODATA	Iterative Self-Organizing Data Analysis Technique
ITA	InnoTech Alberta
JJA	June/July/August
Jul	July
Jun	June
LiDAR	Light Detection and Ranging
max	Maximum
min	Minimum
ML	Maximum Likelihood
MNDVI	Modified Normalized Difference Vegetation Index
NA	Not Available
NBR+	Normalized Burn Ratio Plus
NBR2	Normalized Burn Ratio 2
NDII	Normalized Difference Infrared Index
NDREI	Normalized Difference Red Edge Index
NDVI	Normalized Difference Vegetation Index
OBIA	Object-Based Image Analysis
OSE	Oilsands Exploration
p10	10th Percentile
p90	90th Percentile
PCA	Principal Component Analysis
PTAC	Petroleum Technology Alliance of Canada
RVI	RADAR Vegetation Index
s	Spatial
SAVI	Soil-Adjusted Vegetation Index
SFOC	Special Flight Operations Certificate

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std	Standard Deviation
t	Temporal
TPI	Topographic Position Index
VHR	Very High Resolution
VLOS	Visual Line of Sight

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1.0 INTRODUCTION

Under Alberta's regulatory framework, companies must obtain a reclamation certificate to demonstrate that upstream oil and gas sites have been returned to equivalent land capability and are self-sustaining. Traditionally, this assessment relies on extensive fieldwork, which is labour-intensive, costly, and introduces safety risks, particularly in remote locations. This liability poses a significant challenge to the oil and gas industry in Alberta as it is responsible for reclaiming hundreds of thousands of disturbed sites.

Emerging digital technologies, such as remote sensing offer a viable solution to these challenges. By integrating remote sensing data with advanced analytical algorithms, upstream oil and gas operators can reduce the number of required site visits while maintaining, if not improving, the accuracy and reliability of reclamation assessments. This approach has the potential to significantly cut costs, streamline certification processes, and enhance post-reclamation environmental monitoring.

This project aimed to validate and optimize the use of remote sensing technologies for reclamation certification assessments. By evaluating the outcomes of key technologies such as Light Detection and Ranging (LiDAR), airborne and spaceborne imagery, and derived data products, this research explored their potential in assessing landscape, soil, and vegetation parameters in comparison to traditional field methods. With the growing liability associated with abandoned and orphaned wells in Alberta, estimated at over 172,000 sites, adopting technology-based assessment methods could significantly reduce financial and environmental risks while improving efficiency.

This report summarizes the reclamation assessment results of 44 boreal forest wellsites using remote sensing data in Alberta. These assessments were conducted by three environmental consultants with strong expertise in remote sensing using different analytical tools and techniques to arrive at their conclusions. This diversity of approaches allowed for an evaluation of a broad spectrum of technology-based reclamation assessment methodologies.

While this project focused on upstream oil and gas sites in Alberta and reflects Alberta's regulatory requirements, assessments of human footprints based on remote sensing technologies are relevant in other jurisdictions and other anthropogenic footprints. The results of this project should be broadly useful.

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2.0 METHODS AND DATA

2.1 Site Selection

2.1.1 Phase 1

We, (InnoTech Alberta (ITA)), requested a list of wellsites from the Alberta Energy Regulator (AER) which met the following criteria:

- recent decision dates (2018-2022)
- located primarily in areas where ITA had access to recent LiDAR data from the ABMI (Alberta Biodiversity Monitoring Institute) or Al-Pac (Alberta-Pacific Forest Industries Inc.)
- Located in the boreal region of Alberta

We provided AER with a shapefile of the areas for which recent LiDAR coverage was available. Sites were limited to those identified as wellsites in the spreadsheet provided by AER, which resulted in primarily minimal disturbance Oilsands Exploration Sites (OSE) being identified.

The original intention had been to include both sites that had been approved for reclamation certification and sites that had not passed certification. Unfortunately, there are a very limited number of sites in the AER database that have not been approved, except in relation to administrative deficiencies. This reflects the fact that companies generally do not submit reclamation certification applications that they do not expect to pass.

The list from the AER was further parsed by ITA as follows: Site were restricted to those reclaimed under the forested criteria (i.e. avoiding wetland and peatland sites), and sites that were constructed in 2007 or later to ensure current assessment requirements were followed (Environment and Sustainable Resource Development, 2013).

We categorized sites by majority and minority forest cover type and selected a mix of Aspen, Aspen Mixedwood, Birch (including Mixedwood) and Pine (lodgepole/jack), which reflected the forest types available on the sites. Minority forest cover type did not significantly influence site selection. Sites were assigned to get as close to an even distribution of forest types across the three environmental consultants.

We prioritized the inclusion of "full" disturbance practices, though "minimal disturbance" sites were included eventually because of the limited number of available full disturbance sites. We also prioritized the inclusion of sites of Petroleum Technology Alliance of Canada (PTAC) member companies whenever possible to reflect the participation of PTAC in this project but also included non-member operators to achieve a measure of distribution in consideration of other criteria. Furthermore, we identified the county each wellsite was in and tried to distribute sites

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reasonably equally across contractors based on the number of appropriate sites available in each county.

Finally, a total of 34 sites (Figure 1) were selected and distributed among consultants ensuring that each site was assigned to at least two consultants. We aimed for a reasonably equitable distribution for comparisons between consultants (i.e., consultants 1 and 2, 2 and 3, and 1 and 3). However, due to an error in the site allocation process, this was not the case for Sites 2 and 32, which were only assessed by a single contractor. Additionally, Site 28 received only one assessment as it ended up included in a group of 7 additional sites that Consultant 1 chose to assess beyond the 20 assigned sites.

2.1.2 Phase 2

Phase 2 of this project was initiated in response to requests from Alberta Environment and Protected Areas (AEPA) and the AER to ensure both an opportunity to evaluate 10 additional sites (Figure 1) that had undergone greater disturbance and to validate remote sensing methods where consultants were not aware of the likely reclamation certificate outcome (i.e., pass/fail). It included fully disturbed conventional oil and gas sites ready for reclamation certification and those that were not. "Reclamation certification ready" refers to sites with a completed Detailed Site Assessment (DSA) in 2024 that have not yet been submitted to the AER, but which are considered by the operator to be a “pass”. This approach ensures that consultants remain unaware of the application outcome, maintaining a "blind" assessment. Additionally, sites not considered a pass by the operator (i.e., not ready for a DSA) were included to provide negative cases or “fail” scenarios. All sites were in areas where we had access to the most recent LiDAR data from the ABMI or Al-Pac. Canadian Natural Resources Limited (CNRL) kindly agreed to support this project by providing access to sites based on the selection criteria above.

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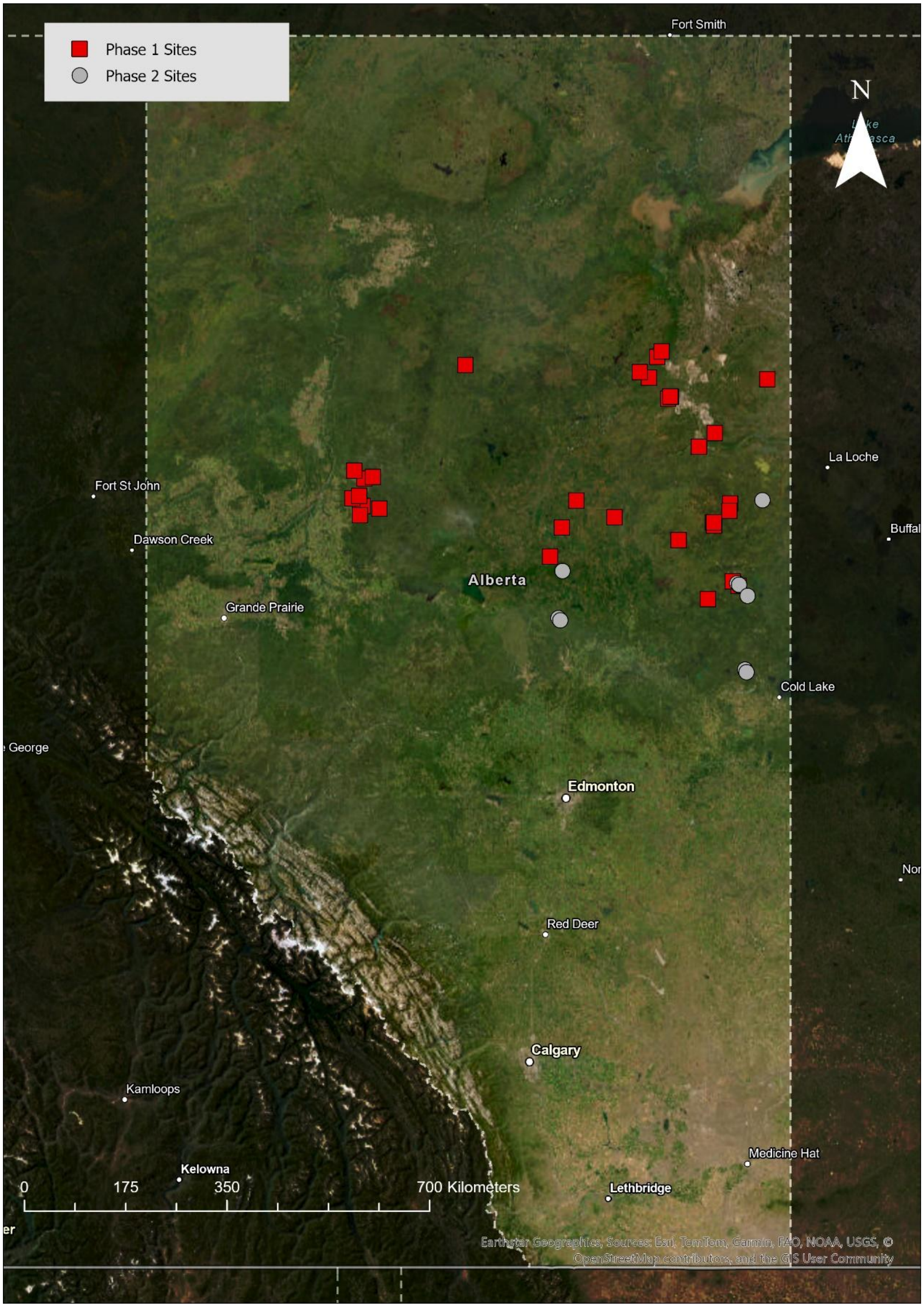

Figure 1. Geographic locations of Phase 1 and Phase 2 wellsites.

2.2 REMOTE SENSING DATA SELECTION

For this project, we acquired very high spatial resolution (VHR) multispectral remote sensing imagery from various sources to ensure sufficient coverage of all wellsites selected for the project. No single source was able to provide imagery at the required spatial resolution, thus it was acquired through SkyWatch (Pléiades, Pléiades-Neo, and Skysat satellites) and Hexagon (aerial imagery). The panchromatic sharpened imagery consisted of red, green, blue, red-edge, and near-infrared bands at spatial resolutions between 0.16 and 0.5 m. When imagery was available from the Pléiades-Neo sensor, raw non-sharpened data were also acquired at a spatial resolution of 1.2 m as well as panchromatic sharpened at a spatial resolution of 0.3 m.

LiDAR data were acquired from:

a. Alberta Pacific Forest Industries Inc. (2017, 2022)

b. Alberta Biodiversity Monitoring Institute (2022)

c. Natural Resources Canada (2017, 2018)[1]

d. Airborne Imaging (2008, 2010, 2011, 2012, and 2013)

e. Altalis (2022).

LiDAR data included point cloud data (except for Natural Resources Canada) as well as Digital Elevation and Surface Models (DEM, DSM) at 1 m resolution. Point cloud data varied between 1.3 points/m^2 (Airborne Imaging 2013 and older), 12 points/m^2 (Alberta Pacific Forest Industries Inc.), and 16 points/m^2 (Altalis).

The data were provided to the consultants via Nextcloud, a data sharing platform hosted by the ABMI. In cases where there were issues accessing the data on Nextcloud, we also provided a SharePoint link to ensure the consultants had access to the data.

2.3 SITE ASSESSMENTS BASED ON REMOTELY SENSED DATA

2.3.1 Introduction

Each consultant was tasked with evaluating oil and gas wellsites using remote sensing data products to assess their reclamation status according to the 2010 Reclamation Criteria for Wellsites and Associated Facilities for Forested Lands (Environment and Sustainable Resource Development 2013). This will be referred to as the "2010 Reclamation Criteria" throughout the document. Additional OSE-specific criteria can be found in the Coal and Oilsands Exploration Reclamation Requirements (Alberta Environment and Parks, 2015). However, in this study, OSE sites were not treated differently from fully disturbed wellsites from a analysis perspective. The

[1] https://open.canada.ca/data/en/dataset/957782bf-847c-4644-a757-e383c0057995

data products included VHR multispectral imagery and LiDAR data acquired by ITA as indicated above. Additionally, consultants could leverage other publicly available and free data products for their analyses. Consultants were allowed to carry out the task according to their own analytical strength and expertise provided they document their approach and rationale for arriving at their conclusions.

2.3.2 Consultant 1

Consultant 1 relied on a quantitative approach to analyse the remote sensing data for reclamation certification-related site assessments. Specifically, Consultant 1 used five separate approaches that quantitatively or qualitatively assessed each wellsite using either different derived datasets or methods, each resulting in a pass, uncertain, or fail decision. These approaches were: **a) Decision Tree Model, b) Spectral Recovery Analysis**, **c) Off-Site Comparison**, **d) Visual Assessment using VHR satellite imagery**, and **e) Visual Assessment using LiDAR data**. The **Overall Decision** represents a consensus of the outcomes from all five approaches.

2.3.2.1 Decision Tree Analysis

A decision tree model was developed to classify wellsites into either reclaimed or not reclaimed. This was done by training the classification algorithm on spatio-temporal features or metrics based on Sentinel-1 and -2 derived multispectral indices commonly used for vegetation monitoring (Table 1). To train the decision tree, 700 wellsites were selected from the ABMI 2021 Human Footprint dataset (ABMI, 2023) based on specific criteria. These criteria included:

- wellsites with abandonment or reclamation dates within the Sentinel-2 image acquisition period (January 1, 2019 to December 31, 2023);
- wellsites located in forested areas;
- proximity to the 34 test sites (10 km buffer zone around all available sites); and
- wellsites must contain between 20 and 80 Sentinel-2 pixels (10 m × 10 m pixel size) to ensure they are comparable in size to the 34 test sites and provide sufficient data to measure spatial variability.

Common descriptive statistics were calculated for each vegetation index by pixel. This was done first for the growing season months (May to September) as well as the summer season (average of June, July, and August). Pixel values were then further aggregated at the site level. The chosen statistics to describe vegetation spatial structure and monthly changes were the average, the median, the minimum and maximum value, the 10 and 90th percentile, and the standard deviation. During model training, 20 key features emerged that were best in distinguishing between reclaimed and not reclaimed sites (Table 2).

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Table 1. Sentinel-1 & -2 derived spectral indices and multispectral bands considered by Consultant 1.

Spectral Index	Spectral Index Full Name	Equation
NDVI	Normalized Difference Vegetation Index	(N - R) / (N + R)
EVI2	Two-Band Enhanced Vegetation Index	2.5 * (N - R) / (N + 2.4 * R + 1)
SAVI	Soil-Adjusted Vegetation Index	2 * (N - R) / (N + R + 1)
MNDVI	Modified Normalized Difference Vegetation Index	(N - S2) / (N + S2)
GNDVI	Green Normalized Difference Vegetation Index	(N - G) / (N + G)
NDREI	Normalized Difference Red Edge Index	(N - RE1) / (N + RE1)
NDII	Normalized Difference Infrared Index	(N - S1) / (N + S1)
NBR2	Normalized Burn Ratio 2	(S1 - S2) / (S1 + S2)
NBR+	Normalized Burn Ratio Plus	(S2 - N2 - G - B) / (S2 + N2 + G + B)
RVI	RADAR Vegetation Index	4 * VH / (VH + VV)

Note: B – Blue (B2), G – Green (B3), R – Red (B4), RE1 – Red Edge 1 (B5), N – Near Infrared (B8), N2 – Narrow Near Infrared (B8A), S1 – Shortwave Infrared (B11), S2 – Shortwave Infrared (B12), VV - Radar Polarization Band (Vertical transmit, Vertical receive), VH - Radar Polarization Band (Vertical transmit, Horizontal receive).

Using an independent sub-sample of the 700 wellsites as a test set, the decision tree model achieved an overall accuracy of 78.5 %. That means that 78.5 % of the time the model correctly classified whether a site was reclaimed or not reclaimed, where probability scores below 50 % were labeled as failed reclamation, scores between 50 % and 60 % indicated an uncertain reclamation status, and scores above 60 % suggested a high probability of successful reclamation.

Table 2. Spatio-temporal features used by Consultant 1 for the decision tree model. For example, Feature 1 reflects the spatial variation (std = standard deviation, s = spatial) of maximum (max = maximum, t = temporal) EVI2 values during June within the wellsite. JJA stands for June, July, August average (representing the summer months).

Feature	Band	Season	Spatial Statistic	Temporal Statistic	Importance Score
1	EVI2	Jun	std_s	max_t	0.407821
2	EVI2	Jul	min_s	p10_t	0.20255
3	B8	JJA	min_s	min_t	0.126628
4	RVI	Jun	p10_s	avg_t	0.076221
5	VH	Jun	std_s	p90_t	0.030975
6	VV	Jul	max_s	p90_t	0.029803
7	NDREI	Jun	std_s	avg_t	0.026117
8	SAVI	Jun	min_s	avg_t	0.02471
9	B8	Jul	std_s	avg_t	0.018139
10	NDVI	JJA	min_s	p10_t	0.010872
11	VH	May	std_s	p90_t	0.009069
12	NDREI	Jun	min_s	min_t	0.008686
13	GNDVI	Sep	min_s	p10_t	0.00806
14	NDII	JJA	p10_s	min_t	0.006677
15	NDVI	Jun	max_s	std_t	0.00584
16	NBR	JJA	min_s	p10_t	0.00268
17	B8	Jul	std_s	p90_t	0.002174
18	RVI	Jun	min_s	p90_t	0.001855
19	NBR	Jun	max_s	std_t	0.00087
20	VV	May	max_s	avg_t	0.000256

2.3.2.2 Spectral Recovery

To assess spectral recovery, Consultant 1 used the publicly available PEOPLE-ER Spectral Recovery Tool[2], an open-source project and analysis package. The Spectral Recovery Tool provides computationally simple, centralized, and reproducible methods to perform spectral recovery analysis of forested sites using Landsat imagery (30 m × 30 m pixel size). Spectral recovery monitors a user chosen spectral index over time, e.g., the NDVI. This approach helps to understand the vegetation's pre-disturbance state and subsequently track its recovery post-disturbance. Using the Spectral Recovery Tool, Consultant 1 created a time series of images from 2000 to 2023 for all wellsites provided by InnoTech Alberta. Spectral recovery was assessed during the summer months for the NDVI, MNDVI and NBR+ spectral indices (Figure 2).

[2] https://people-er.github.io/spectral-recovery/

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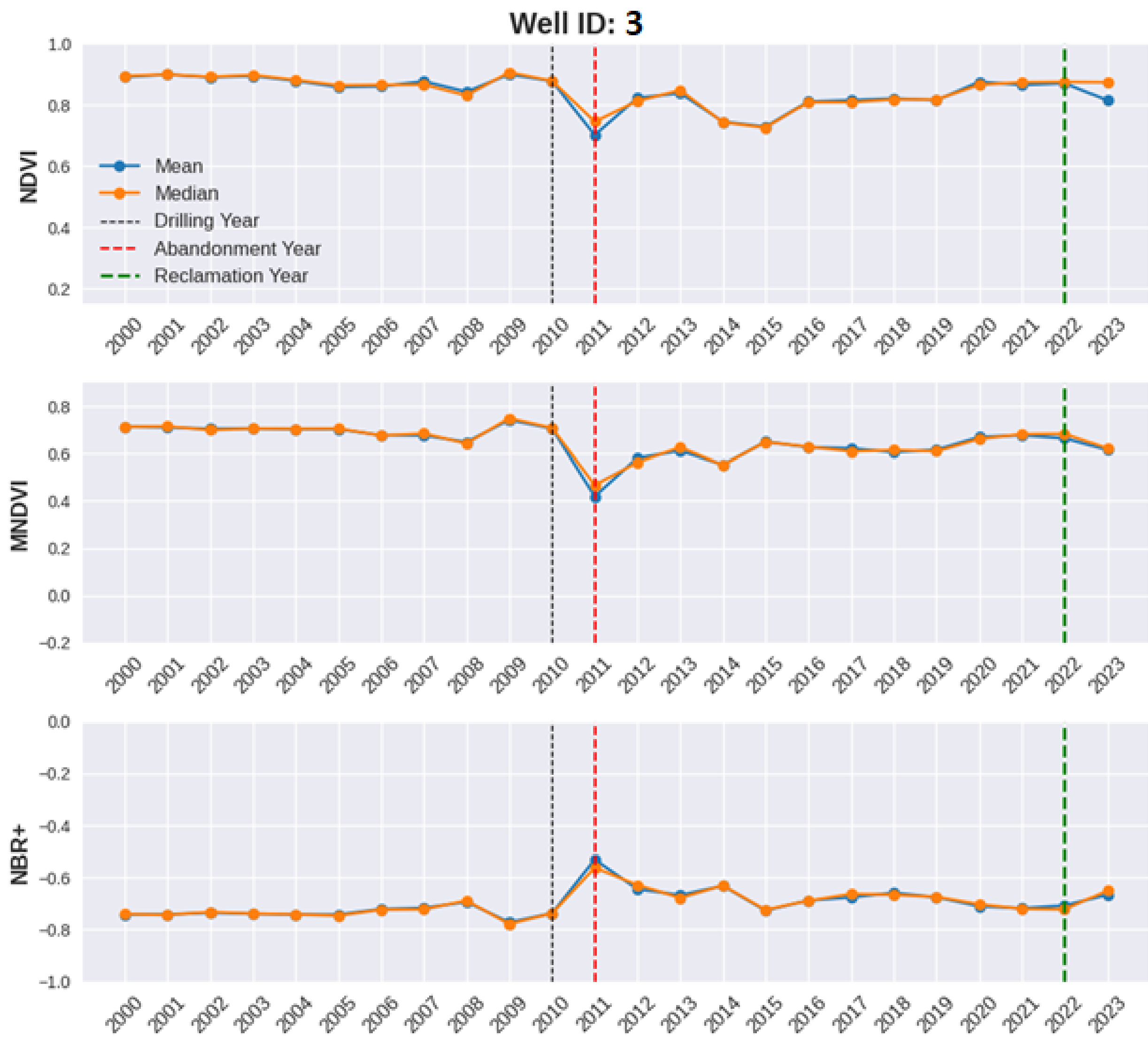

Figure 2. Example of a spectral recovery assessment for wellsite 3 before, during and after disturbance. Three spectral indices were used, NDVI, MNDVI and NBR+. See **Table 1** for full name and formula.

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2.3.2.3 Offsite Comparison

To conduct an off-site comparison, a manually delineated reference area was chosen adjacent to each of the 34 wellsites. The reference area was a similar sized area within a 200 to 300 m buffer around the assessed wellsite and comprised of an undisturbed forested area. Sentinel-2-based time series were generated separately for the wellsite and reference area to capture the temporal variations in spectral features. These time series were compared during the growing season (May to September) from 2019 to 2023. Each time step indicates a value on a specific date when Sentinel-2 imagery was available. These time series were assessed in two ways: analytically using the NDVI, MNDVI, NBR2, and NBR+ spectral indices, as well as visually (Figure 3, Figure 4). The Euclidean distances between the reference area and the wellsite for all four spectral indices were calculated across the growing season months (May to September), resulting in a gap value. A gap value of less than 1 was interpreted as similar temporal patterns between the reference area and wellsite; a gap value larger than 1.5 was taken as evidence of a significant difference between the reference area and the wellsite with respect to vegetation conditions.

2.3.2.4 Wellsite Condition - Visual Assessment (VHR)

Using the ITA-provided VHR imagery, a visual (qualitative) assessment of the wellsite condition and surrounding area was also performed. This step provided comparative information, adding further evidence to the overall assessment decision (Figure 5).

2.3.2.5 Surface Landscape Visual Assessment (LiDAR)

Using LiDAR point clouds along with DEM and DSM, wellsites were assessed for elevation and, topographic position index (TPI) anomalies, as well as vegetation height and percent vegetation cover conditions (Figure 6). This approach enabled the assessment of surface landscape issues that could impact woody vegetation responses, such as drainage conditions.

2.3.2.6 Overall Decision

The overall decision was a synthesis of all five approaches in which each assessment was given equal weight (Table 3). The outcomes of the five approaches were either quantitative (data driven) or qualitative (visual interpretation).

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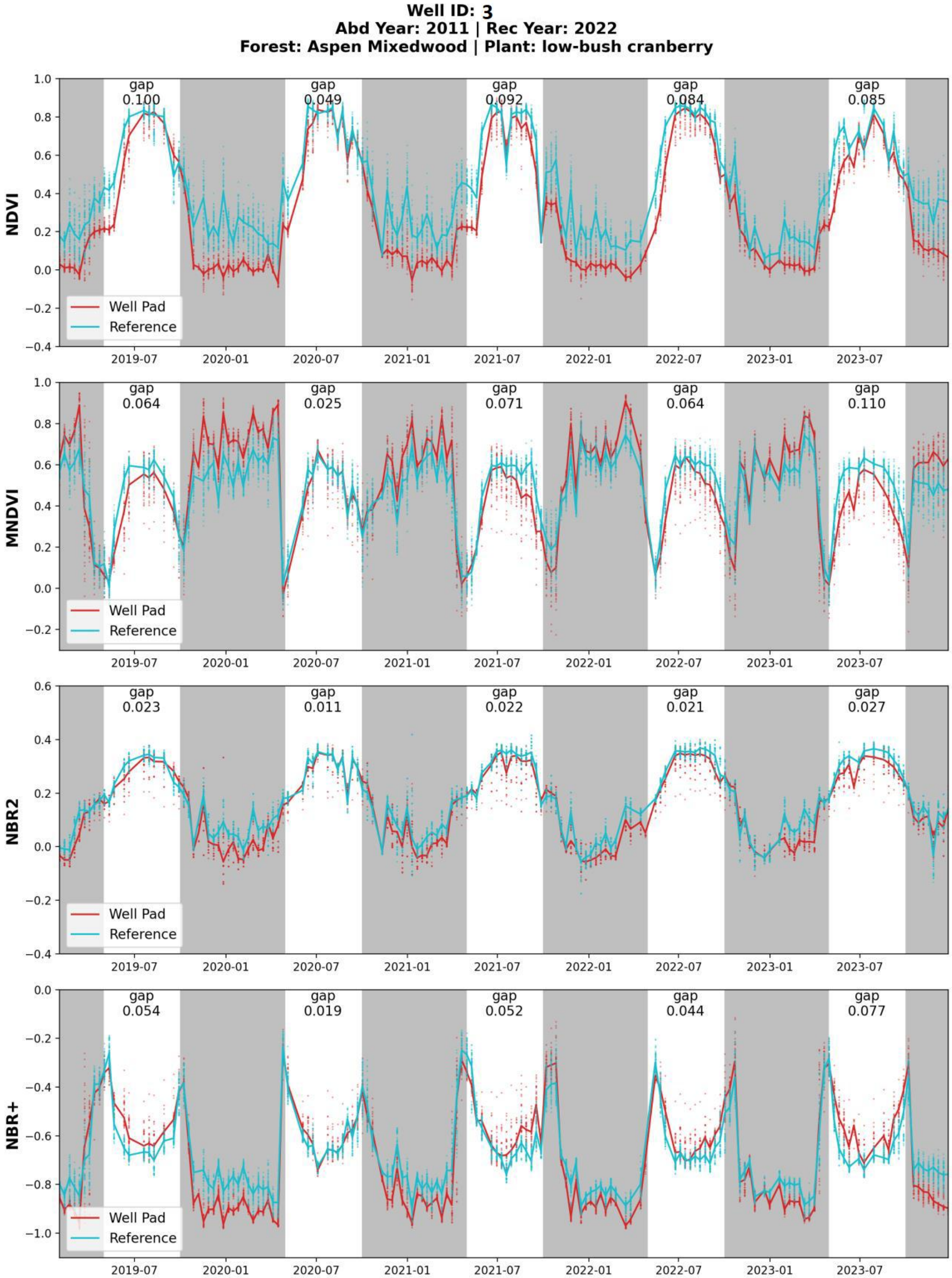

Figure 3. Example of a reference area and wellsite comparison for wellsite 3 during the growing season months (May to September) using four spectral indices, NDVI, MNDVI, NBR2, NBR+. Gap values indicate whether a wellsite showed different (> 1.5) or similar vegetation conditions (<1) during the growing season months (white areas).

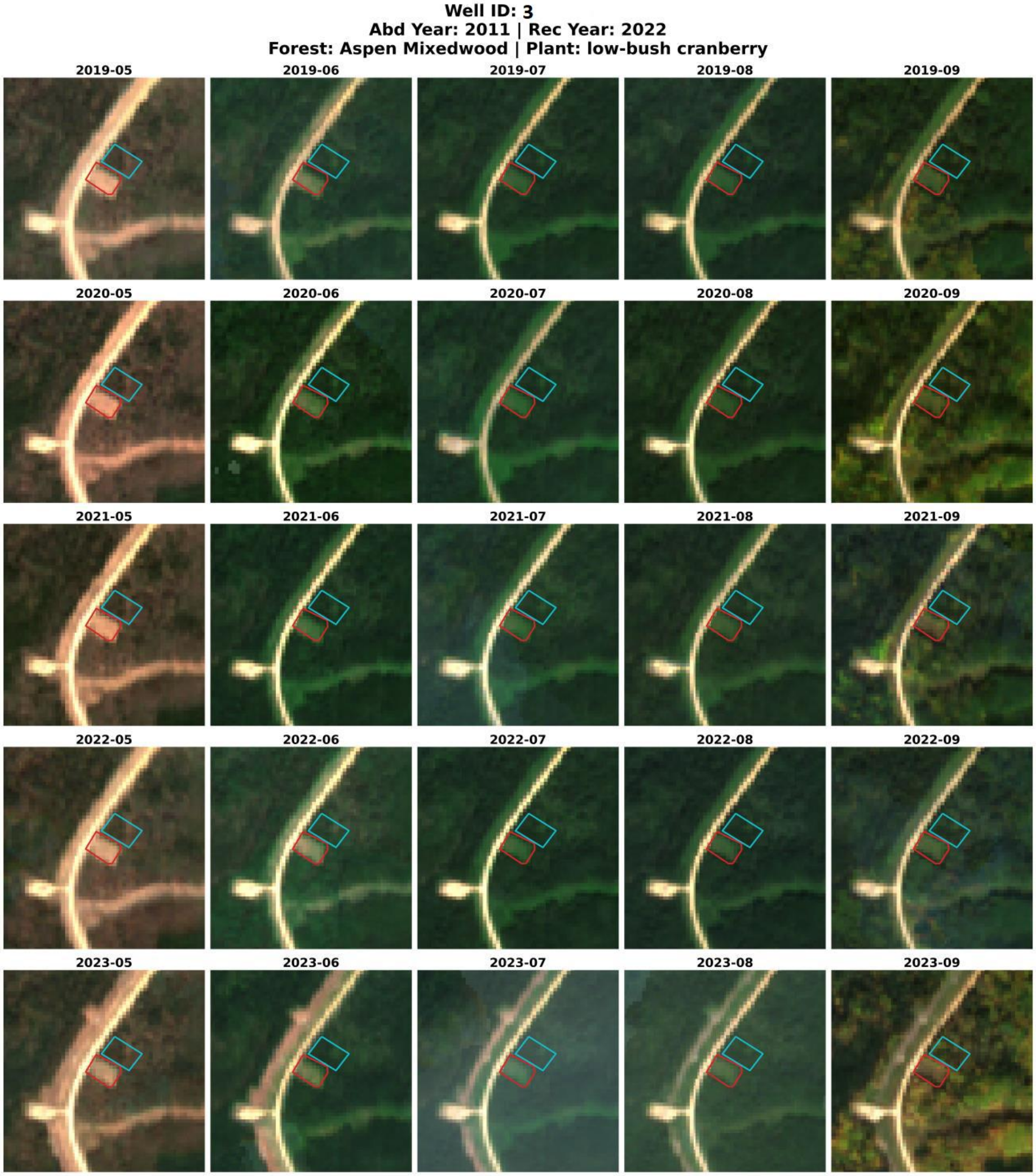

Figure 4. Example of images used in visual assessment of the vegetation conditions on the reference area (blue polygon) and wellsite 3 (red polygon) during the growing season months (May to September) from 2019 to 2023, both before and after the year of reclamation.

Figure 5. Example of very high-resolution image of wellsite 3 (red polygon) and the surrounding area. September 17, 2023 SkySat image provide by ITA.

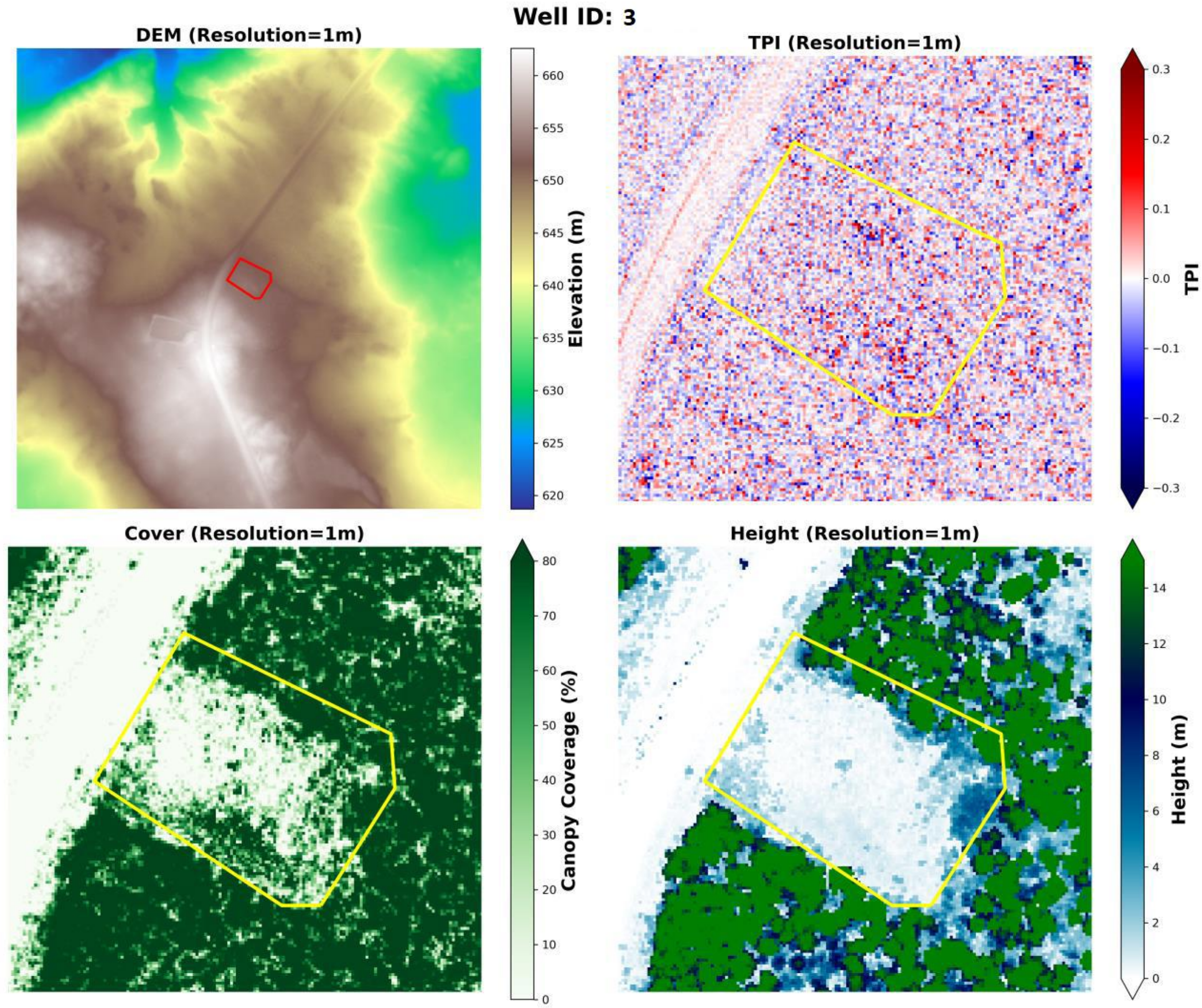

Figure 6. Example LiDAR point cloud derivatives, digital elevation model (DEM), topographic position index (TPI), percent canopy cover, and tree height for wellsite 3.Yellow and red polygons outline wellsite area.

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Table 3. Example summary, assessment criteria and conclusions by Consultant 1 for wellsite 3. See also Figure 2, Figure 3, Figure 4, Figure 5, and Figure 6 for imagery supporting the technology-based assessments results.

Wellsite ID: 3	
Background Information	
Operator:	
Criteria:	Forested
Provincial Zone:	Green Area
Designation Type:	Public Lands
Legal Land Description (ATS):	
Survey Date:	2010-11-04
Construction Date:	2010-12-03
Abandonment Date:	2011-01-10
Revegetation Date:	2014/08/12 & 2016/07/26
Reclamation Completion Date:	2016-07-19
Location Assessed	
Area assessed:	Well site
UTM Zone (NAD83)	
Northing:	
Easting:	
Revegetation Approach	Forested: Planted
Technology-based Assessment Results	
Decision Tree	Pass; Probability Score of Pass = 67.3%
Spectral Recovery	Pass; All three spectral indices have largely returned to pre-disturbance levels.
Comparison with Off-Site Location	Pass; Vegetation indices of well pad show very similar pattern with reference off-site area and no obvious gaps observed.
Visual Assessment (VHR)	Fail; The well pad was largely dominated by bare soil, with vegetation primarily observed around the edges.
Visual Assessment (LiDAR)	Pass; The height data indicate the absence of significant tall vegetation within the well pad, while the canopy density data shows that ~40% of the area is covered by dense vegetation.
Final Status	Pass

Classification: Protected A

2.3.3 <u>Consultant 2</u>

Consultant 2 leveraged their expertise in remote sensing and environmental site assessments (ESA) to develop a process to inform reclamation certification, within the constraints of available remote sensing multispectral and LiDAR data, and other site or baseline information. They determined that a Phase 1 ESA desktop assessment (Alberta Environment, 2001) would be an effective starting point for creating a decision checklist informing the 2010 Reclamation Criteria (Environment and Sustainable Resource Development, 2013). Remote sensing approaches were then developed to inform their decision checklist (Table 4).

In their remote sensing technology assessment, Consultant 2 explored various machine learning approaches such as Object-Based Image Analysis (OBIA), Iterative Self-Organizing Data Analysis Technique (ISODATA), and Maximum Likelihood (ML) classification algorithms to identify "like-areas". This can help to discover object clustering or heterogeneity on the wellsite, which may warrant further investigation. Consultant 2 also used Principal Component Analysis (PCA) to reduce redundancy in the multispectral sensor data and to extract the most informative features as inputs for the classification algorithms. However, the reliability of their algorithm was limited by the availability of training data both spatially and temporally and this limited the application of these machine learning approaches for this project. Nonetheless, Consultant 2 was able to test the ISODATA and ML approaches on a few wellsites within the current project by having the model learn from the baseline reference data available to them.

With the challenges associated with using more complex approaches, Consultant 2 chose to use a key multispectral derivative, the NDVI, to assess vegetation on wellsites (Figure 7).

The available LiDAR data were used to generate a canopy height model (CHM), which is derived from the difference between the provided DEM and DSM. The CHM allowed the consultant to assess the vegetation cover characteristics of the wellsite. Additionally, TPI was calculated to evaluate the surface evenness of the wellsite.

Consultant 2 further used the Derived Ecosite Phase v2.0 provided by the Government of Alberta (Agriculture and Forestry, 2020) to assess the wellsite relative to its ecosite. The Derived Ecosite Phase dataset uses Alberta Vegetation Inventory and Lidar-derived datasets to classify sites on the basis of ecological characteristics.

Table 4. Example assessment criteria developed by Consultant 2 and conclusions for wellsite 19. See also Figure 7 for imagery supporting the technology-based assessments results.

Location			
Site name	19		
LSD			
Data Sources	**Description**	**Date**	
Topographic	LiDAR	2013	
Photo	Pan sharpened Pleiades-Neo Multi-spectral image	8/21/2022	
Multispectral	TOA corrected 4 BAND Pleiades-Neo Multi-spectral image	8/21/2022	
Assessment Criteria		**Yes/No**	**Site Assessment Conclusion**
1. Sign of Surface staining and contamination e.g. salt crystals visible in images		No	No contamination or spill recorded at site ground from near infrared or ultraviolet bands shows no anomalous reflectance.
2. Presence of industry artifacts (large mechanical parts, off site storage pits, tanks)		No	Site is in a complex ecological unit. There are no visible artifacts anywhere on the site.
3. Canopy re-vegetation consistent with Ecological unit		Yes	Site is classified in what would have been pre-disturbance units in the DEP layer across several complex units. It appears to be returning to the dominant unit called a c1 (Labrador tea-mesic - Pj-Sb) The new growth of pine and black spruce is visible with some bare spots in the middle that are consistent with a change in ecological unit according to the pre- disturbance data. The unit is drier due to a higher topographic position, and future monitoring may reveal an acceleration in the pine stands canopy growth with increased cover from a taller adjacent canopy.
4. NDVI Indicates healthy spectral response		Yes	Appears to have a mixed (healthy-poor) NDVI spectral response. On the higher slopes of the northeast quadrant of the wellsite Jack Pine and Black Spruce stands growing in sandy soils appear to be struggling to grow. The lower areas in the remainder of the site appear to be growing healthy Aspen stands consistent with the adjacent canopy outside the wellsite.
5. Topography consistent with adjacent units to enable site drainage		No	According to TPI the site is half laid in a position higher from its surroundings. See Map 6 Annotations
6. Presence of other active sites upstream within 1 km		Yes	Appears to be active sites west and east within 200 metres of Assessment Site ID.
7. Has spill been recorded at site		No	No reports from AER or Abadata
8. Site has ground water well within 1km		No	Reviewed Alberta Water Well Information Database (AWWID)
9. Recommendation		Fail	**Additional comments:** Struggling pine stands on dry higher ground are evident in the northeast part of the wellsite and is expected. Overall vegetation is growing in a positive trend. Potential drainage issues noted from topography models.

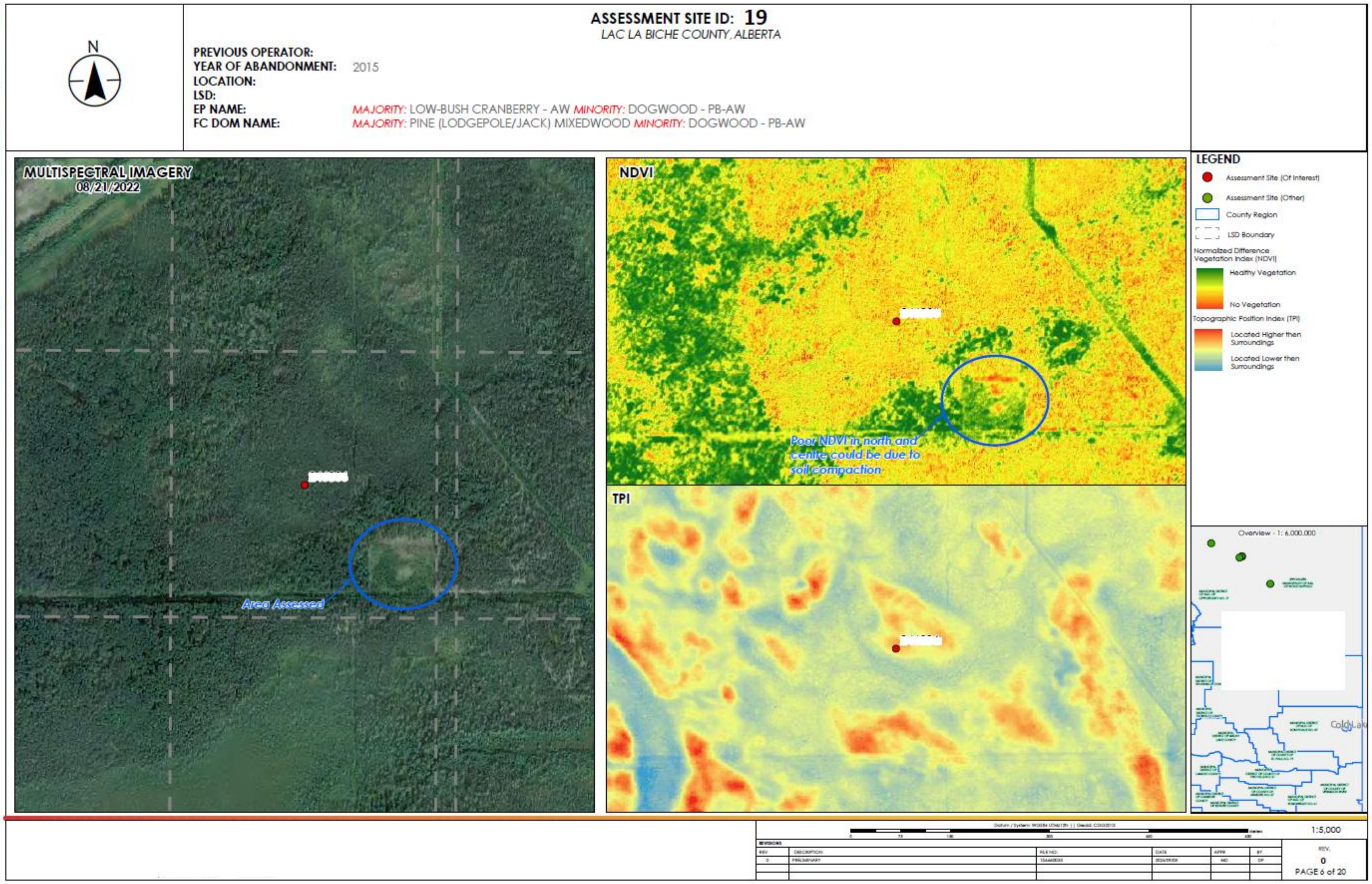


Figure 7. Example of remote sensing imagery assessment by Consultant 2 included multispectral (derived NDVI and visual examination) as well as LiDAR analyses, including the topographic position index (TPI). White boxes have been used to cover sensitive information.

2.3.4 Consultant 3

Consultant 3 leveraged their extensive experience and knowledge in reclamation work for the oil and gas sector to support professional judgement-based approaches. Remote sensing and LiDAR data results were evaluated, and, when inconclusive, professional judgement was used to make pass/fail decisions. This professional judgment also enables Consultant 3 to address issues related to noxious weeds and agronomic species, which cannot be directly resolved through remote sensing and LiDAR data at the spatial resolutions and temporal scales provided. While Consultant 3 also considered traditional supervised or unsupervised classifications to assess vegetation, they ultimately rejected these options because they require significantly more site knowledge and existing training data for vegetation classification, or labour-intensive post-classification of results.

Consultant 3 split their assessments up into two parts: (a) **vegetation analysis**, (b) **terrain analysis**. The results of these two parts will inform the final assessment.

2.3.4.1 Vegetation Analysis

Within the vegetation analysis, they performed a vegetation extent assessment (Figure 8), a vegetation height assessment by height class and within DSA grid cells (Figure 9, Figure 10) and provided an ecosite map (Figure 11) using the Derived Ecosite Phase v2.0 (Agriculture and Forestry, Government of Alberta, 2020).

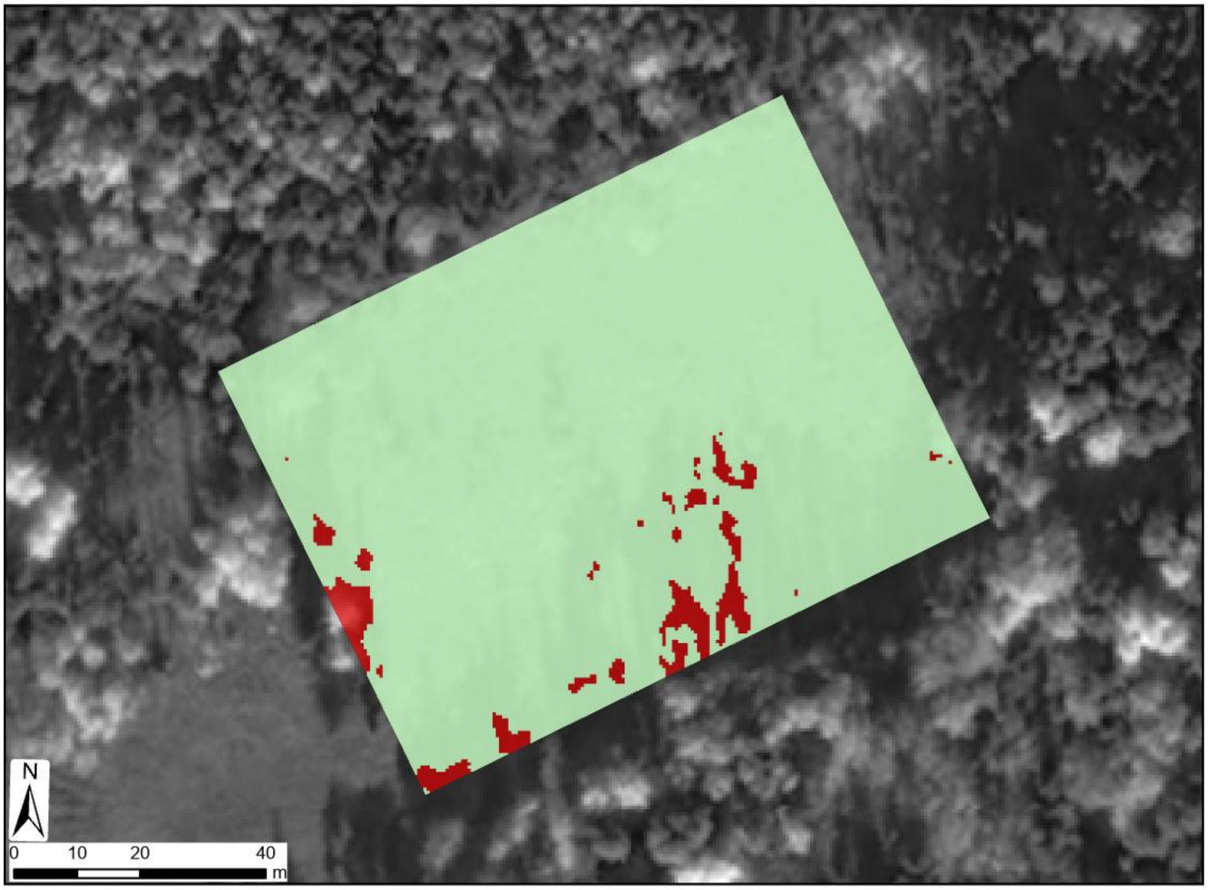
The vegetation extent assessment identified which areas were vegetated and which areas were not. This binary decision was driven by a thresholded NDVI value determined by visual interpretation of the spectral imagery at each wellsite, focusing on areas of bare earth and sparse vegetation compared to denser, established vegetation. Once this site-specific NDVI threshold was established, sites were categorized as vegetated or not vegetated (Figure 8).

The vegetation height assessment was done using the provided LiDAR data at 1m horizontal resolution. A CHM was generated by subtracting the DEM and DSM, creating a detailed map of the vegetation height across the wellsite (Figure 9, Figure 10). To distinguish between different types of vegetation, Consultant 3 classified the CHM data into four classes: Bare or Very Low Vegetation (<25 cm – soil, grasses, moss), Low Vegetation (25-50 cm – grasses, small shrubs), Moderate Vegetation (50-150 cm – established shrubs, immature trees), and Tall Vegetation (>150 cm – immature or established trees).

To provide context for the assessment of vegetation development, Consultant 3 generated an ecosite map for each wellsite using the Derived Ecosite Phase v2.0 provided by the Government of Alberta (Agriculture and Forestry, Government of Alberta, 2020) (Figure 11).

Classification: Protected A

Vegetation Cover

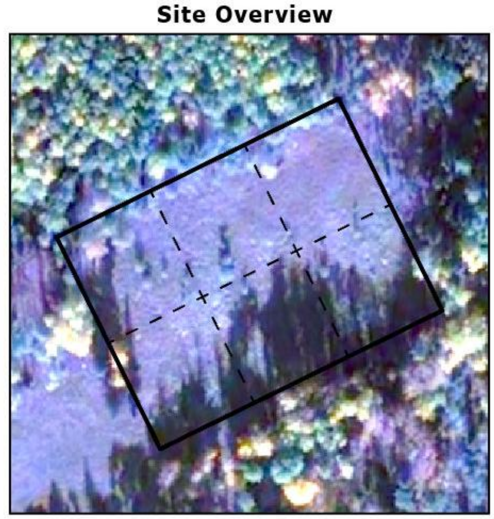


Class	Area	Site Area(m2)	Area (%)
Vegetated	7206.2	7495.1	96.14
Sparsely Vegetated	288.9	7495.1	3.86

Sparsely Vegetated

Vegetated

Site Overview



Vegetation Cover derived from Multispectral image. Background image and Site Overview are from the Optical Acquisition image.

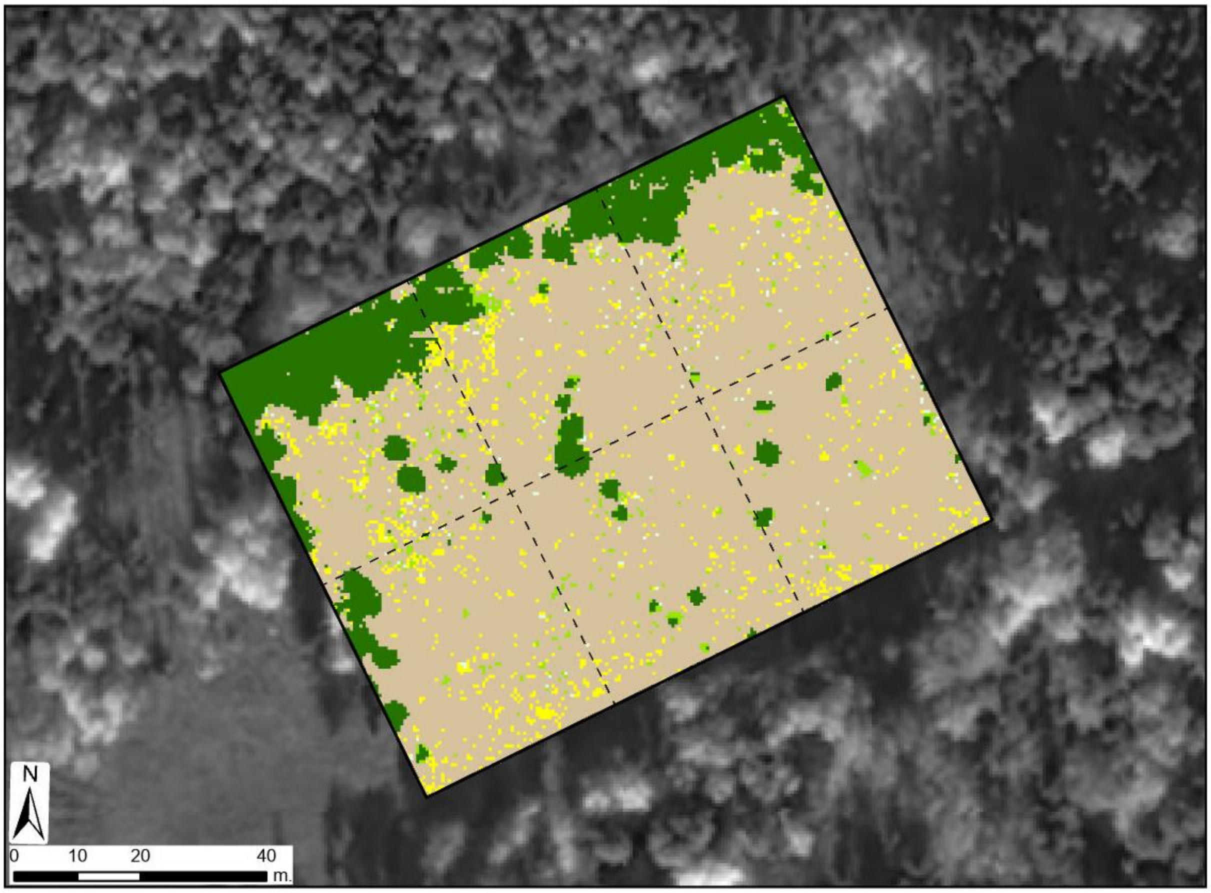
Optical Acquisition Date	Site Footprint Source
28Sep2022	Dispostion

SiteID	LSD	Spud Date	Abandoned Date	Construction Type
17		2010	2010	FULL

Figure 8. Example vegetation extent assessment by Consultant 3 for wellsite 17. Red areas indicated sparsely vegetated, whereas green areas are vegetated.

Classification: Protected A

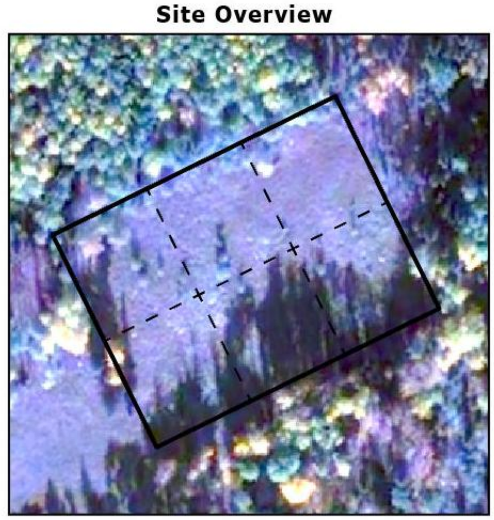
Vegetation Height, by Site



Class Name	# of Features	% Cover
Class 1 - Vegetation Less than 25cm	103	77.2%
Class 2 - Vegetation 25cm to 50cm	825	4.9%
Class 3 - Vegetation 50cm to 75cm	160	0.6%
Class 4 - Vegetation 75cm to 150cm	303	1.8%
Class 5 - Vegetation Greater than 150cm	62	15.5%

Vegetation Height derived from LiDAR Acquisition. Background image and Site Overview are from the Optical Acquisition image.

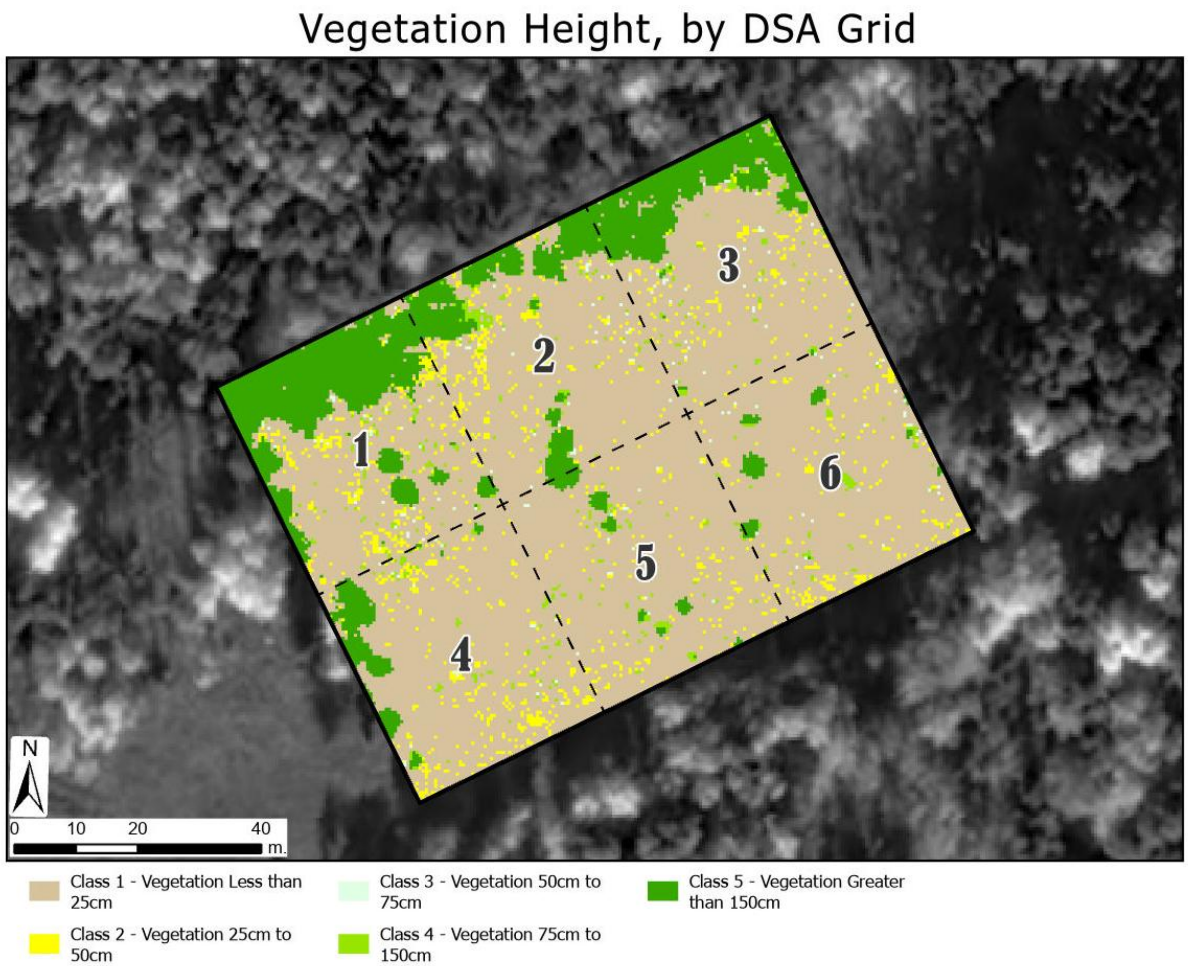
Site Overview



Optical Acquisition Date	LiDAR Acquisition Date	Site Footprint Source
28Sep2022	2017	Dispostion

SiteID	LSD	Spud Date	Abandoned Date	Construction Type
17		2010	2010	FULL

Figure 9. Example of vegetation height assessment (LiDAR) by Consultant 3 for wellsite 17. Site-level vegetation count and cover reported for each class of vegetation height.



Feature Count, by Class

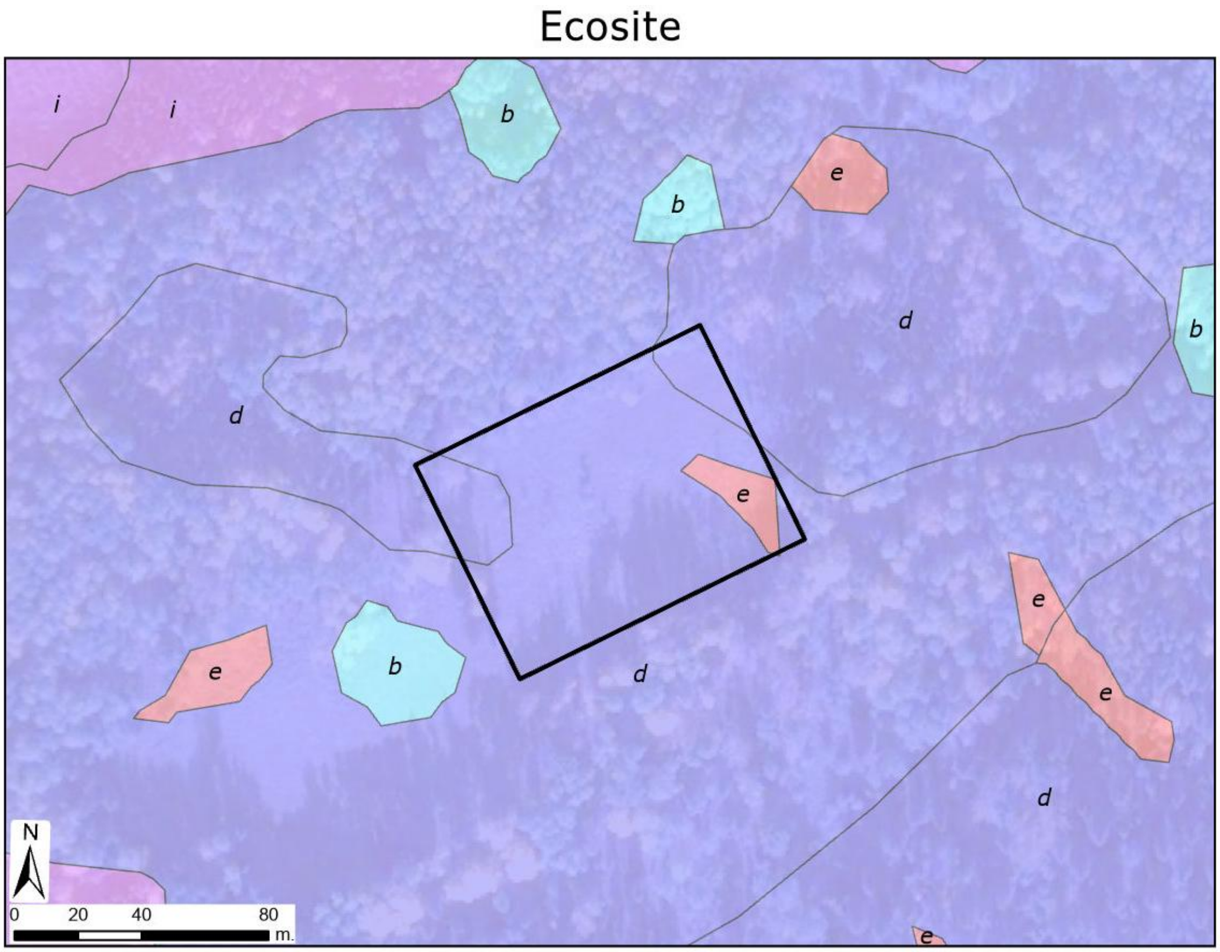
DSA Grid Cell	Class 1	Class 2	Class 3	Class 4	Class 5
1	29	150	37	64	19
2	28	142	35	61	11
3	29	123	32	53	7
4	16	188	17	45	9
5	2	126	15	58	12
6	7	122	29	33	12

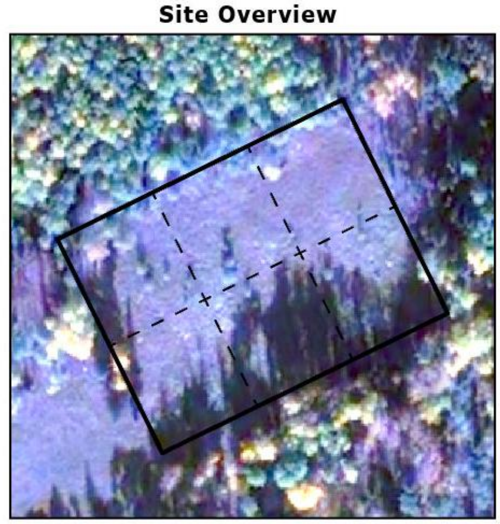
Percent Cover, by Class

DSA Grid Cell	Class 1	Class 2	Class 3	Class 4	Class 5
1	53%	6.2%	0.8%	1.8%	37.9%
2	74%	5.3%	0.8%	2.3%	17.5%
3	69.6%	3.5%	0.8%	1.9%	24%
4	83.8%	6.7%	0.4%	1.5%	7.2%
5	91.6%	3.3%	0.4%	1.8%	2.8%
6	90.7%	4.4%	0.6%	1.4%	2.6%

SiteID	LSD	Spud Date	Abandoned Date	Construction Type
17		2010	2010	FULL

Figure 10. Example vegetation height assessment (LiDAR) by Consultant 3 for wellsite 17. Each wellsite is divided into six Detailed Site Assessment (DSA) grid cells and vegetation count and cover reported for each cell and height class.





Ecosite boundaries obtained from Derived Ecosite Phase, Version 2 from open.alberta.ca. Background image and Site Overview are from the Optical Acquisition image.

Optical Acquisition Date	Site Footprint Source
28Sep2022	Dispostion

SiteID	LSD	Spud Date	Abandoned Date	Construction Type
17		2010	2010	FULL

Figure 11. Example ecosite map for a wellsite by Consultant 3.

Classification: Protected A

2.3.4.2 Terrain Analysis

To assess the terrain, Consultant 3 used the provided LiDAR data to generate a topographic site assessment with 10 cm contour lines (Figure 12). This information was then used to determine whether wellsites exhibited uneven surfaces that could lead to surface water accumulation or potential water-related erosion which could hinder woody vegetation development. These terrain-related issues may not be identifiable during visual interpretation of optical imagery.

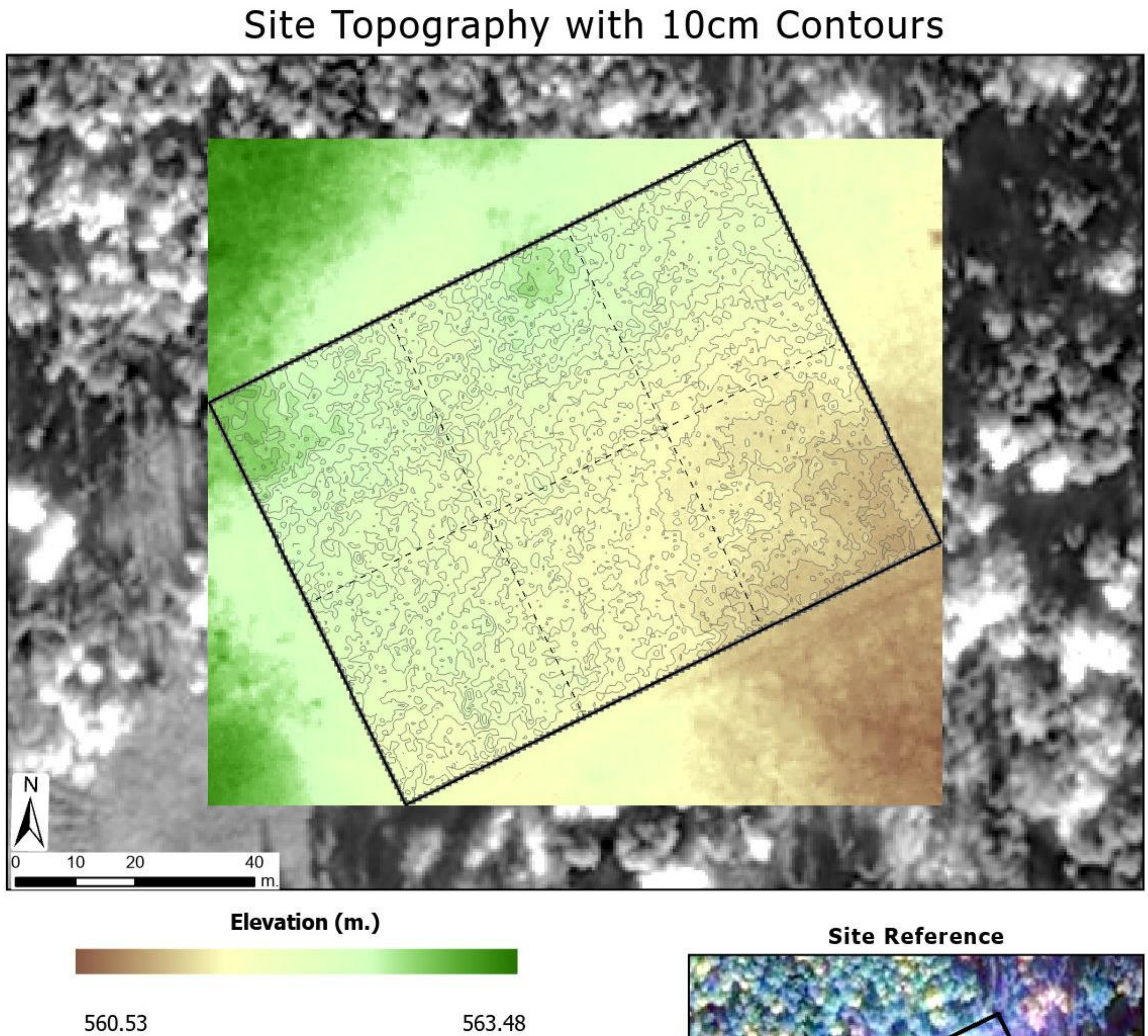
2.3.4.3 Final Assessment

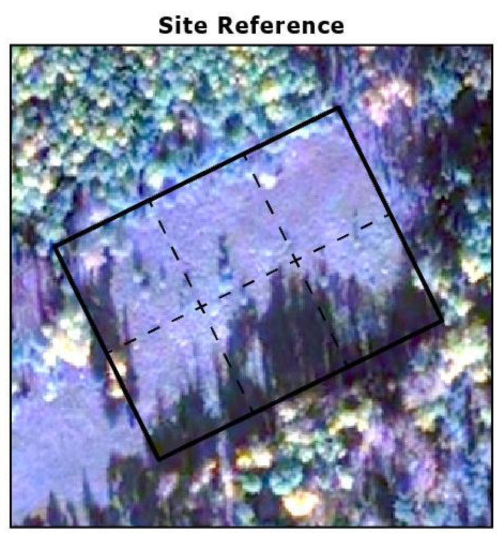
The final assessment results were synthesized in Table 5 in accordance with the 2010 Reclamation Criteria (Environment and Sustainable Resource Development, 2013).

Table 5. Example summary, assessment criteria and conclusion by Consultant 3 for wellsite 17. See also Figure 8, Figure 9, Figure 10, Figure 11, and Figure 12 for imagery supporting the technology-based assessments results.

Site	17
Pass/Fail	Pass
Vegetation Cover	No issues
Density/Cover Class	Grid 2 lower, but actual densities on ground would be greater than what LiDAR can detect
Disturbance Intensity	Low
Ecosite Limitations	None
Optical Imagery	Displays forest development better than LiDAR
Landscape/Soils	No issues
Professional Judgement Required	Yes
Comments	Bare areas are due to shadowing. Actual tree and shrub densities are greater than what LiDAR can detect; however, LiDAR is showing well-distributed clumps of tree/shrub growth throughout each grid. Given the remoteness of the site, most ground cover will be native graminoids such as *Calamagrostis canadensis*. Without LiDAR data showing various plant community structures, it would be hard to determine the pass or fail status for a site constructed within a transition period where agronomic grasses could still have been seeded.

Classification: Protected A





Site Topography derived from LiDAR Acquisition. Background image and Site Overview are from the Optical Acquisition image.

Optical Acquisition Date	LiDAR Acquisition Date	Site Footprint Source
28Sep2022	2017	Dispostion

SiteID	LSD	Spud Date	Abandoned Date	Construction Type
17		2010	2010	FULL

Figure 12. Example topographic site assessment showing 10 cm contours derived from LiDAR data for a wellsite.

Classification: Protected A

3.0 RESULTS

3.1 SUMMARY

A total of 44 wellsites across phases 1 and 2 of the project were assessed by three consultants. All consultants received the same remote sensing data products but could also use other publicly available data for their analyses. Each consultant analysed the data based on their remote sensing expertise, resulting in a variety of approaches, each with its own strengths and resulting recommendations. These approaches ranged from highly data-driven and quantitative methods to qualitative assessments of the provided high-resolution imagery, and the use of professional judgment to evaluate reclamation criteria not reliably detected by the remote sensing data.

3.2 PHASE 1

Phase 1 consisted of 34 wellsites, with each consultant assessing 20 sites that had already received a reclamation certificate (Table 6). Consultant 1 chose to add 7 additional sites at their own discretion. Sites were assigned so that each site was assessed by at least two consultants. In two cases (Site 2 and 32) only one consultant assessed the site due to an error in the site allocation process. In addition, Site 28 was only assessed by Consultant 1 as it was included in their voluntary additional 7 sites assessed. Consultants evaluated each site to give a "fail" or "pass" rating. Consultant 1 added an "uncertain" rating for their assessments (Figure 13).

It is important to note that recommendations for a "fail" or "uncertain" rating should not be seen as criticism of an in-field DSA outcome of "pass". Instead, these ratings indicate that, based on the remote sensing assessment, the consultant would need more information to determine if the site should truly "pass". The information they were missing would often be part of an in-field data collection effort. Consultants in this project erred on the side of caution in their evaluations, thereby minimizing false positives both in this application and in future assessments.

Consultant 1 passed 23 out of the 27 assessed sites (85.2 %), issued 2 "uncertain" ratings (7.5 %), and 2 "fail" ratings (7.5 %). All their assessments consisted of five sub-assessments, each receiving its own "pass" / "fail" / "uncertain" decision (Figure 13) and a unified "pass" across all sub-assessments was not required for a site to be considered a "pass".

Consultant 2 failed 8 out of the 20 assessed sites (40 %) and passed 12 (60 %). Consultant 3 passed all sites (100 %).

Classification: Protected A

Table 6. Wellsites assessed in Phase 1 and the provided remote sensing imagery. Empty cells represent unknown values.

Site ID	Disturbance	Construction	Abandonment	Reclamation	Assessment	Very High Resolution Imagery	LiDAR
1	Minimum/OSE	Nov-14	Jan-15	Jan-15	Aug-18	2022-2023	2022
2	Minimum/OSE	Nov-14	Jan-15	Jan-15	Aug-18	2022-2023	2022
3	Full	Dec-10	Jan-11	Jul-16	Oct-21	2023	2017
4	Minimum/OSE	Dec-12	Mar-13	Aug-16	Jul-18	2020-2023	2017
5	Minimum/OSE	Jan-13	Mar-13	Aug-16	Jul-18	2023	2017
6	Minimum/OSE	Jan-13	Mar-13	Aug-16	Jul-18	2023	2017
7	Minimum/OSE	Jan-13	Mar-13	Aug-16	Jul-18	2023	2017
8	Minimum/OSE	Jan-13	Mar-13	Mar-13	Aug-21	2022	2013
9	Minimum/OSE	Jan-12	Mar-12	Mar-12	Aug-21		
10	Minimum/OSE	Jan-11	Mar-11	Mar-11	Aug-18	2022-2023	2011, 2022
11	Minimum/OSE	Feb-11	Mar-11	Aug-14	Various 2016,2017		
12	Minimum/OSE	Mar-11	Mar-11	Aug-14	Various 2016,2017	2022-2023	2022
13	Full	Jan-10	Feb-10	Aug-14	Aug-21	2022	2011
14	Minimum	Feb-10	Mar-10	Mar-10	Aug-14		2013
15	Full	Jan-10	Mar-17	Mar-17	Sep-19	2022	2012
16	Full	Jan-10	Mar-10	Mar-10	Aug-17	2022	
17	Full	Feb-10	Mar-10	Mar-10	Jul-18	2022-2023	2017
18	Full	Nov-10	Jan-11	Jan-16	Jul-19	2020-2022	2017

19	Full	Oct-10	Jul-15	Mar-18	May-21	2022	2017
20	Minimum	May-10	Mar-11	Mar-11	Sep-15	2020-2022	2011
21	Full	Feb-12	Mar-12	Feb-13	Sep-19	2022	2013
22	Minimum	Mar-12	Sep-15	Sep-15	Aug-21	2022	
23	Minimum	Dec-11	Mar-13	Aug-14	Sep-18		2022
24	Minimum	Feb-13	Mar-13	Mar-13	Sep-17		2022
25	Full	Jan-12	Jan-12	Feb-12	Jul-18	2023	2017
26	Full		Mar-11		Sep-17		2013
27	Minimum/OSE	Jan-16	Feb-17	Feb-17	Aug-21	2022	2013
28	Full	Jan-11	Mar-12	Mar-12	Aug-17		
29	Full	Dec-10	Jan-11	Jan-11	Sep-19	2022	2013
30	Full	Feb-12	Jan-17	Jan-17	Oct-18	2021-2023	2017
31	Minimum	Feb-12	Mar-12	Feb-13	Aug-19	2022	2013
32	Minimum/OSE	Dec-10	Mar-11	Jul-14	Jul-18		2018
33	Minimum/OSE	Nov-14	Jan-15	Jan-15	Aug-18	2022-2023	2022
34	Minimum/OSE	Nov-14	Jan-15	Jan-15	Aug-18	2022-2023	2022

Classification: Protected A

In evaluating the differences in outcomes between consultants, it was clear that there were more consistencies than differences and that uncertainties in remote sensing approaches existed for all consultants. For instance, when Consultants 1 and 2 differed in their assignment of "fail" ratings, Consultant 1 often had sub-assessments (Figure 14) which aligned with the assessments made by Consultant 2. Consultant 3 often used professional judgement to pass a site that was failed by other consultants because the provided data was considered inadequate to determine a "pass" rating (Table 7).

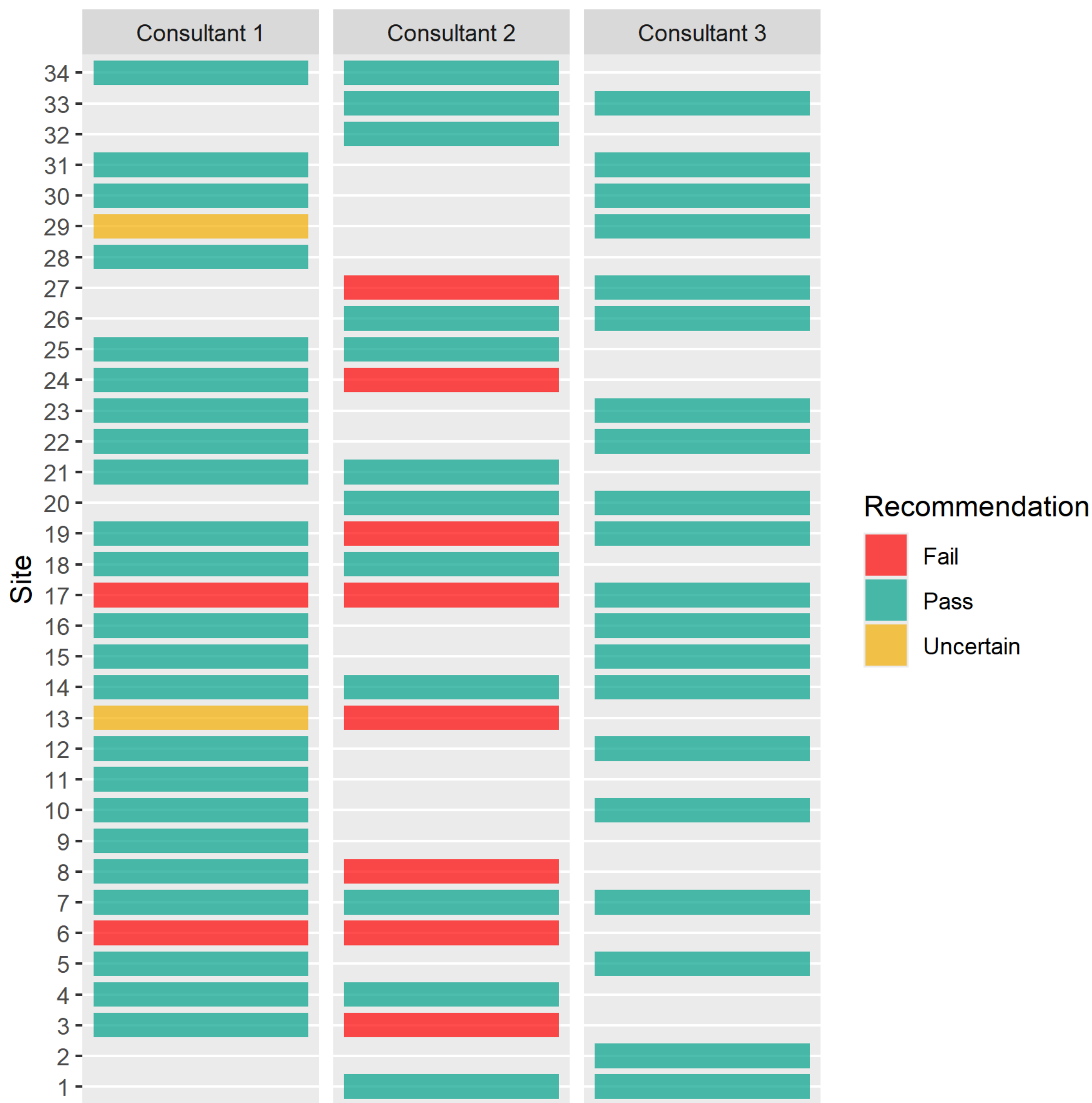


Figure 13. Phase 1 assessment results by site and consultant.

Classification: Protected A

This outcome is also observable in cases when all three consultants issued a pass (e.g. Site 7), Consultant 1 rated all sub-assessments with a "pass" and Consultant 3 did not require the use of professional judgment. This site had characteristics allowing all consultants to issue a pass, such as sufficiently tall trees to fully utilize the LiDAR imagery.

Both Consultants 1 and 2 issued a "fail" for Site 6, which had received a reclamation certification. Consultant 1 had four sub-assessments rated as "fail", except for the visual assessment (VHR), which was assigned an "uncertain" (Figure 14). Upon reviewing the publicly available detailed DSA for this OSE site, it was discovered that the photo description included in the DSA was incorrect, and the site was indeed not ready for a reclamation certificate.

Table 7. Contrasting the "fail" recommendations by Consultant 2 with the "fail"/"uncertain" sub-assessments of Consultant 1 and whether Consultant 3 added "Professional Judgement" to their decision.

Sites labeled "fail" by Consultant 2	Consultant 1	Consultant 3
27	Site not assessed by Consultant 1	Professional Judgement: Yes
24	Visual assessment (VHR): Uncertain	Not assessed
19	No "uncertain" or "fail" sub-assessments	Professional Judgement: Yes
17	Comparison with off-site location: Fail Visual assessment (VHR): Fail Visual assessment (LiDAR): Fail	Professional Judgement: Yes
13	Decision Tree: Uncertain Comparison with off-site location: Uncertain Visual assessment (VHR): Fail Visual assessment (LiDAR): NA	Not assessed
8	Visual assessment (VHR): Uncertain Visual assessment (LiDAR): NA	Not assessed
6	Decision Tree: Fail Spectral Recovery: Fail Comparison with off-site location: Fail Visual assessment (VHR): Uncertain Visual assessment (LiDAR): Fail	Not assessed
3	Visual assessment (VHR): Fail	Not assessed

Classification: Protected A

Figure 14. Phase 1 final decision and sub-assessments by Consultant 1. NA means these assessments were not available due to data availability. This was primarily the case when the LiDAR data were older than the abandonment of the site.

When comparing failed and passed remote sensing assessments with in-field DSAs, it became apparent that failed sites often only had young trees growing (from natural regeneration or planted seedlings). These trees were not observable above taller grasses and other herbaceous species. This suggests that sites passing very early by in-field DSAs do not exhibit woody regeneration of an adequate age or size to be reliably detected by remote sensing imagery or LiDAR (Figure 15).

Figure 15. Two views of Site 17, a site that received a reclamation certificate but was rated "fail" by Consultants 1 and 2. Consultant 3 passed the site but had to apply professional judgment (see also **Table 5**). As can be seen, woody vegetation is developing (shrubs and smaller trees); however, this appears to be difficult to detect using remote sensing technologies using the provided remote sensing imagery. Photos were taken from publicly available DSA accessed with the OneStop Application Query Tool: https://www1.aer.ca/PubDocs/#/application-query.

3.3 PHASE 2

Phase 2 consisted of the analysis of conventional wellsites with construction dates ranging from 1969 to 2015, exhibiting minimal to full disturbance levels. Assessment information provided by Canadian Natural Resources Limited (CNRL) for these sites was utilized in ITA's analysis but was not available to consultants. CNRL deemed six out of the ten sites (Sites 5 to 10) ready for a DSA and application for reclamation certification. Four sites (Sites 1 to 4) were assessed as not ready for a DSA, requiring more time for the regeneration of woody vegetation (Table 8, Figure 16).

Phase 2 assessments were generally much more variable, especially for sites not considered ready for DSAs (Figure 17). This uncertainty can likely be attributed to the lack of woody vegetation at those sites or the presence of significant herbaceous vegetation and grass cover, which likely inhibits the development of woody vegetation and its detection by remote sensing imagery. For sites considered ready for DSAs (Sites 5 to 10), the assessment variability was greatly reduced. This general observation was also seen in the sub-assessments of Consultant 1 (Figure 18).

For example, when looking at Site 5, a site ready to be submitted for reclamation certification, the consultants' assessments received two "fail" and one "pass" assessment (Figure 19). Woody vegetation is present across the site but barely reaches above the herbaceous and grass cover, likely contributing to the varying assessment outcomes. This suggests that sufficient woody vegetation growth is required to achieve reliable remote sensing outcomes relative to early post-reclamation in-field assessments.

Classification: Protected A

Table 8. Wellsites assessed in Phase 2. Sites 1 to 4 (in red) were not ready for a Detailed Site Assessment (DSA). Sites 5 to 10 underwent a DSA and were considered likely to pass a reclamation certification assessment. Empty cells represent unknown values.

Site ID	Status	Construction Date (m-y)	Years in operation	Abandonment Date (m-y)	Reclamation Date (m-y)	Level Of Disturbance	CNRL Assessment
1	Produced from 2000-2005	Nov-99	5	Feb-16	Feb-22	Stripped soils, repaired contour/cut and fill, replaced soils. Tree planted Aug 2022	more regen time for woody species
2	Produced from 1995-2009	Feb-15	14	Jan-22	Jan-22	Stripped soils, repaired contour/cut and fill, replaced soils. Tree planted Aug 2022	more regen time for woody species - some agronomic and weed species present
3	Did not produce	Jan-69		Jan-10		Unknown reclamation practices, likely minimum disturbance. Natural regeneration	More regen time needed for woody species - some bare areas
4	Observation well	Feb-15					more regen time for woody species
5	Built not drilled	Dec-14			Feb-21	Full disturbance. Padded site - pad was removed and site recontoured	DSA ready
6	Produced from 2001-2008	Jan-01	9	Mar-23		Min disturbance construction and reclamation. Natural regeneration	DSA ready
7	Built not drilled	Sep-94				Unknown	DSA ready
8	Produced from 2001-2006	Dec-00	9	Mar-23		Min disturbance construction and reclamation. Natural regeneration	DSA ready
9	Produced from 1997-2004	Feb-97	8	Feb-07		Min disturbance construction and reclamation. Natural regeneration	DSA ready
10	Produced from 2001-2006	Feb-85	6	May-10	Feb-18	Stripped soils, repaired contour/cut and fill, replaced soils. Tree planted July 2019	DSA ready

Classification: Protected A

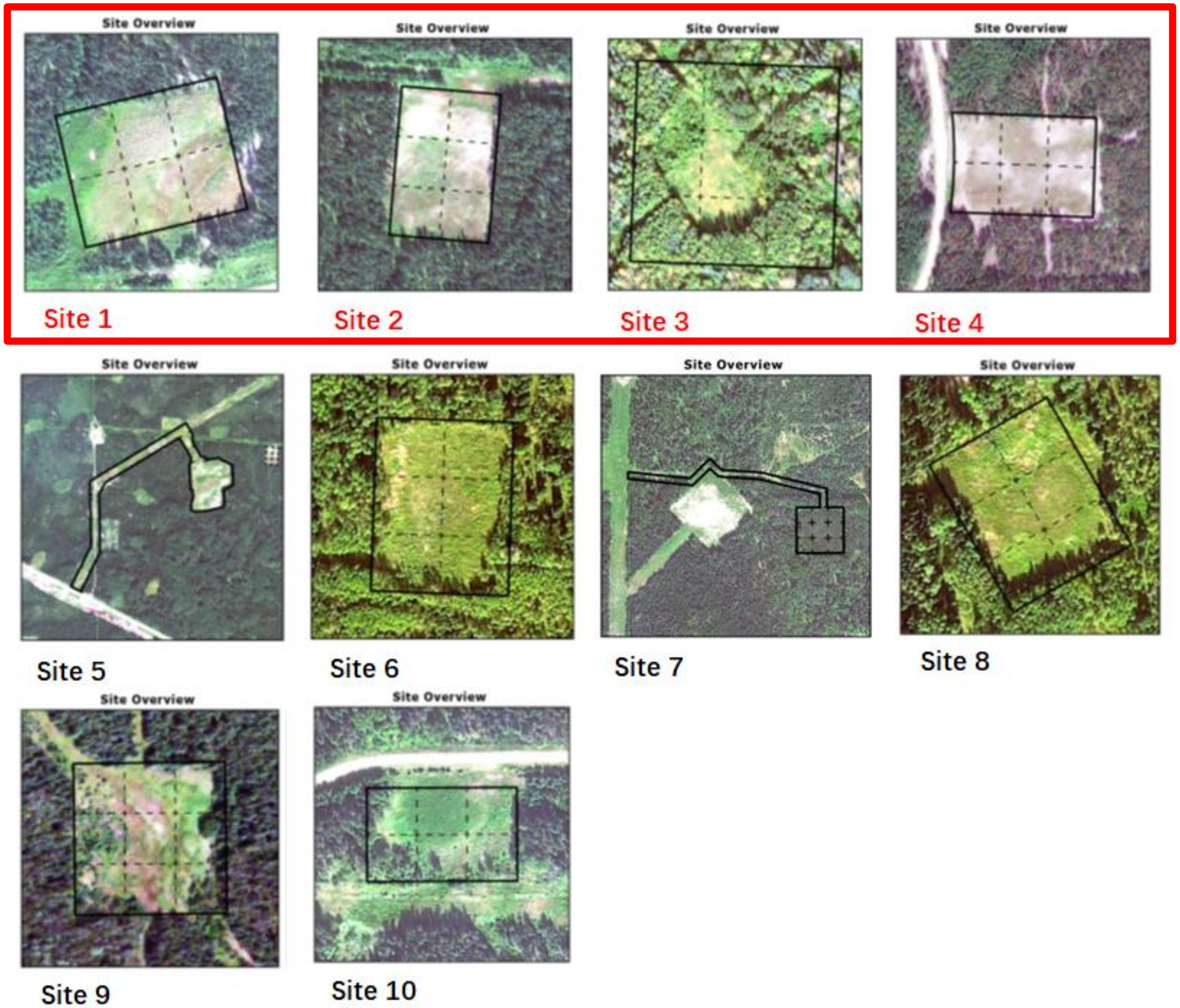


Figure 16. Overview of the very high-resolution imagery for the 10 selected sites. Sites 1 to 4 (outlined in red) are sites that were not ready for a Detailed Site Assessment (i.e., 'no pass'). Image credit: Consultant 3.

Classification: Protected A

Figure 17. Phase 2 assessment of 10 wellsites conducted by Canadian Natural Resources Limited (CNRL) and three remote sensing specialists (Consultant 1,2,3). CNRL's assessment was based on in-field evaluations indicating whether sites were ready to be submitted for reclamation certification ('pass') or needing more vegetation regeneration time ('no pass').

Classification: Protected A

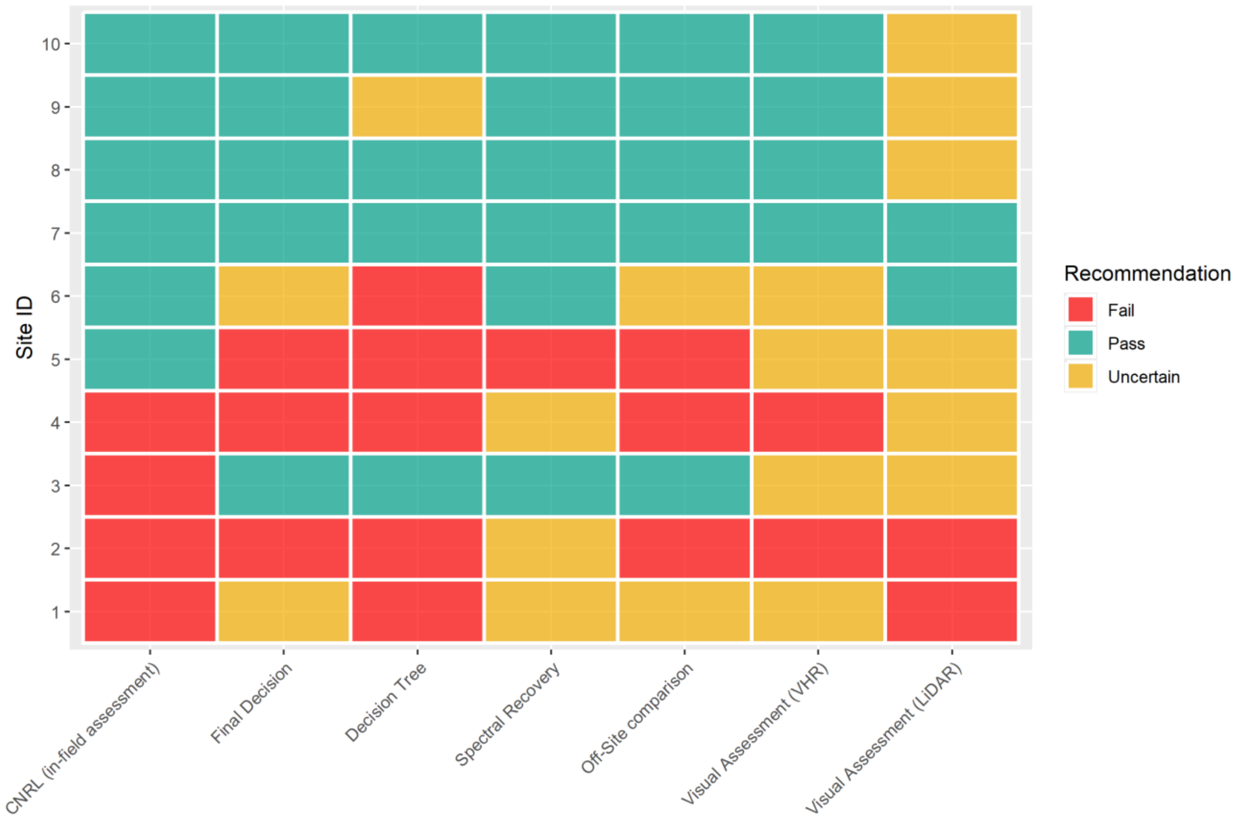


Figure 18. Phase 2 final decision and sub-assessments by Consultant 1 and CNRL assessments.

Figure 19. Two views of Site 5, which had a DSA completed and received mixed assessments from the consultants. Woody vegetation is present across the site but barely reaches above the herbaceous and grass cover. Photos were taken from DSAs provided by Canadian Natural Resources Limited (CNRL).

On the other hand, Site 8 was rated “pass” by all consultants and the photos in Figure 20 show that woody vegetation is present and starting to reach above the herbaceous vegetation and grass layer.

Figure 20. Two views of Site 8 that were rated “pass” by all consultants. Woody vegetation is present above the herbaceous and grass vegetation layer. Photos were taken from DSAs provided by Canadian Natural Resources Limited (CNRL).

Lastly, Site 10 (Figure 21) was another site that received a pass by Consultants 1 and 2. Consultant 3 however decided to rate this site as a “fail” primarily due to the potential that noxious weeds and agronomic species may be present on site (application of professional judgement). Consultants 1 and 2 were not directly assessing the risk of noxious weeds or agronomic species presence in their assessments.

An interesting observation is that Consultant 1 rated Site 3 as a “pass”, while both Consultant 2 and Consultant 3 failed the site. The reason for this discrepancy is that the data-driven approaches of Consultant 1 likely did not pick up on the small bare area in the centre, which is surrounded by tall and healthy trees (see Site 3 in Figure 16). However, this is not surprising since their decision tree model was trained on wellsite characteristics studied in Phase 1 and was not optimized for the new and quite different wellsite characteristics in Phase 2, i.e., mostly low disturbance and smaller sized OSE sites vs. larger often heavily disturbed conventional wellsites with construction dates going back as far as 1969 (Table 8)

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Figure 21. Two views of Site 10 assessed by all three consultants . Consultant 1 and Consultant 2 rated this site as a “pass” whereas Consultant 3 rated this site as “fail”, primarily due to the high likelihood of noxious weed presence as well as a relatively low regeneration rate given its year of abandonment. Photos were taken from DSAs provided by Canadian Natural Resources Limited (CNRL).

Consultant 2 and Consultant 3 also made interesting observations about Site 3. From Consultant 2: “Clear that little to no tree canopy present and while NDVI shows positive chlorophyll response, the absence of trees since drilling activity stopped in 1969 indicates the site may have been used as a staging area (or similar) for many years prior to its recorded abandonment in 2010. The site is full of interesting contradictions and warrants further investigation.” Consultant 3: “Disturbance only on teardrop area but has been disturbed since abandonment in 2010.

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Recent imagery shows reduction in tree growth compared to 2017 Google Earth image, suggesting the site has been re-disturbed. Site too complicated to analyse using RS data only."

Consultant 2 only rated two sites as "fail," and those ratings agreed with the in-field site assessment by CNRL. However, Consultant 2 also rated two sites as "pass," which, based on the in-field assessments, were not ready for a DSA. Consultant 2 was in full agreement with CNRL for the sites that received a DSA.

Consultant 3 rated very conservatively in Phase 2, mostly due to the high probability of noxious weeds and agronomic species that may be present on these sites. The reason for this is that most of the sites were constructed pre-2007. During this time, agronomic species and grasses were often seeded to quickly cover the site and prevent soil erosion (Alberta Environmental Protection, 1995). The problem, however, was that those sites stagnated in succession towards the pre-disturbed state (adjacent control sites). Starting from 2007, the reclamation criteria changed, resulting in a major shift away from seeding agronomic species (Alberta Sustainable Resource Development, 2007; Environment and Sustainable Resource Development, 2013) to a focus on establishing native herbaceous and woody species.

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4.0 DISCUSSION

This report summarizes the results of wellsite reclamation certification assessments based on remote sensing data in the boreal forest region of Alberta. These assessments were conducted by three environmental consultants with strong expertise in remote sensing data analysis and interpretation, each using different tools and techniques to ensure comprehensive evaluations. By testing the application of key technologies like LiDAR, airborne and spaceborne imagery, and derived data products, this project highlighted both the opportunities and limitations of using remote sensing to assess landscape, soil, and vegetation parameters compared to traditional in-field methods. The goal of the project was to determine whether remote sensing data can help assess if wellsites meet the regulatory requirements for a reclamation certificate.

Our results showed that remote sensing technologies can provide critical information necessary to decide whether a wellsite meets the regulatory requirements for a reclamation certificate. All environmental consultants were able to make quantitative and qualitative assessments of elevation and topographical anomalies of the soil surface, as well as revegetation success across the entire wellsite, including reference sites. Furthermore, it was possible to count stems and quantify canopy cover for the entire wellsite, provided sufficient time had passed since reclamation and the establishment of woody vegetation.

However, our results also revealed ongoing limitations in how and when remote sensing approaches should be applied. While these technologies provide valuable tools for monitoring and assessing human disturbances over time, current spatial resolutions limit their ability to reliably identify very young woody vegetation, particularly when it is similar in height to surrounding herbaceous and grass species. Additionally, the methods used in this project were not able to differentiate between desired herbaceous species and undesired or invasive agronomic and weed species, except when supplemented with professional judgment (see further below).

That said, these limitations are technical rather than fundamental and are likely to be overcome as remote sensing technology continues to advance. As satellite spatial and temporal resolution improves, these challenges will become easier to address. For example, narrow-band, very high-resolution hyperspectral imagery may soon provide a viable solution. Furthermore, ongoing advancements in machine learning algorithms and artificial intelligence for classification tasks will further enhance the opportunities for evaluation of sites using remote sensing data.

The use of drones presents another potential alternative for capturing very high-resolution imagery at low altitudes. However, current Canadian regulations restrict drone operations to within visual line-of-sight (VLOS). Exceptions for beyond visual line-of-sight (BVLOS) flights require a Special Flight Operations Certificate (SFOC). Recognizing the constraints this imposes,

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Transport Canada has proposed new regulations to facilitate routine BVLOS operations. These amendments would allow drones weighing up to 150 kg to operate BVLOS in sparsely populated areas, at low altitudes, and in uncontrolled airspace without the need for an SFOC. If enacted, these changes could significantly enhance large-scale forest reclamation assessment efforts by enabling drone flights over vast areas without requiring an operator on-site.

Currently, the risk of undesirable plants on reclaimed wellsites can still be assessed using professional judgment. Higher risk can be assigned to wellsites located near rights-of-way, access roads, and other disturbances, where the likelihood of noxious weeds and undesirable vegetation is greater. Additionally, wellsites abandoned before 2007, when seeding agronomic species was still a common reclamation practice, as well as younger wellsites near those older sites, are at higher risk of hosting noxious weeds and agronomic species. Sites with very low risk of undesirable plants and clear evidence of woody plant growth may not require a site visit, whereas sites with medium or high risk, or those showing slow or stalled growth, would warrant further in-field assessment.

Lastly, all consultants emphasized the importance of access to site history information, including herbicide treatments, seedling plantings, re-disturbance events, and precise drilling and abandonment dates.

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5.0 CONCLUSIONS

In summary, remote sensing technologies are a valuable tool that can complement in-field assessments, provide quality control, and support the monitoring of site progress over time. Our results demonstrate that remote sensing can inform assessment of reclaimed sites as per the 2010 Reclamation Criteria (Environment and Sustainable Resource Development, 2013), including stem counts, the distribution of woody vegetation across the wellsite, and assessments of elevation and topographic anomalies of the soil surface. However, remote sensing technologies are currently unable to clearly differentiate between desired and undesired herbaceous species, an important assessment point under the 2010 Reclamation Criteria (Environment and Sustainable Resource Development, 2013). While professional judgment can be used in such cases, based on wellsite history and location, remotely sensed data alone remain insufficient for this task at present.

Based on our findings and discussions with the consultants, we conclude that for remote sensing to be used without in-field assessment, sites should be 5 to 7 years post-reclamation to enable reliable assessments of woody vegetation regrowth and other key parameters. The 2010 Reclamation Criteria (Environment and Sustainable Resource Development, 2013) set minimum requirements to ensure sites are prepared such that desired reclamation outcomes are likely to be achieved. If these initial criteria are met, operators can obtain a reclamation certificate soon after site abandonment, before the 5- to 7-year period when remote sensing approaches become most reliable. In such cases, in-field assessments will likely remain the preferred method until remote sensing technologies improve further, or until very high-resolution LiDAR and hyperspectral imaging can be conducted via BVLOS drone operations.

Another key consideration is the importance of well-timed LiDAR and optical multispectral imagery acquisition across and within years. These are crucial for accurately assessing reclamation success and capturing seasonal and year-to-year variability. While recent and high resolution LiDAR data may not always be available for specific sites, multispectral imagery is more accessible, with satellites able to be tasked to capture specific regions at key times of the year.

Finally, remote sensing technologies offer a promising approach for evaluating the more than 172,000 abandoned wellsites in Alberta that still require reclamation certification. A classification system that rapidly sorts sites into “passes,” “uncertains,” and “fails” would allow for more efficient allocation of resources, both time and financial, by focusing in-field assessments on sites where further evaluation is most needed.

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6.0 RECOMMENDATIONS

While remote sensing data can be leveraged as indicated in this report, the project identified some key risks that are important to be aware of. Commonly available airborne LiDAR and spaceborne multispectral imagery currently cannot detect small woody vegetation within the herbaceous and grass species layer, or measure species composition, including desirable and undesirable species (i.e. agronomics, weeds, etc.). Consequently, a remotely assessed and recently reclaimed wellsite (on or after June 1, 2007) may fail the vegetation assessment based on the 2010 Reclamation Criteria, even if it meets all requirements and would have passed through an in-field assessment. This occurs when woody vegetation is present but has not progressed adequately leading to false negative assessments. This is unlikely to be the case for in-field assessments. To lower the risk of false negatives, it is recommended to use remote sensing assessments only on sites that have had at least 5 to 7 years for establishment and growth, with access to LiDAR at the upper end of this 5 to 7-year time window.

Conversely, remote sensing assessments may pass a wellsite (reclaimed on or after June 1, 2007) with undesirable species present, which would not pass using in-field assessments, hence leading to false positives. However, the risk of false positives can be minimized by considering site history and the remoteness of the wellsites as outlined above. Furthermore, older sites that have progressed adequately and show evidence of canopy closure are generally associated with a reduction in herbaceous species and grasses in general and are likely of low risk for undesirable species (i.e. agronomics, weeds, etc.).

This means that for oil and gas operators, using remote sensing technologies too early after reclamation poses a higher risk of not achieving a reclamation certificate (false negative), with associated financial implications. From an ecological perspective, there is no risk, as the site meets all criteria when assessed in-field. Conversely, receiving a reclamation certificate despite the presence of undesirable species on sites may result in the withdrawal of the reclamation certificate if audited by the AER and subsequent requirement to meet reclamation criteria. Ecologically, the presence of undesirable species poses a risk and can stall or halt the reclamation trajectory.

Lastly, there is a risk of misinterpretation of remote sensing assessments by the regulator. To maximize transparency, it is strongly recommended that remote sensing consultants provide clear explanations and justifications for their methodologies and outcomes. This ensures accessibility for reviews and audits. Detailed documentation, including metadata, data sources, processing steps, and any assumptions made during the analysis, enhances transparency and helps regulators understand the context of the analysis.

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7.0 APPLICATION

The key challenge in applying remote sensing approaches to reclamation certification is the inability to assess the extent of woody vegetation establishment on wellsites during the first few years after reclamation. The first 5 to 7 years are frequently dominated by grasses and herbaceous species making it difficult to assess stem counts as required by the 2010 Reclamation Criteria. This is primarily because commonly available airborne LiDAR and spaceborne multispectral imagery is not able to resolve this level of detail, at least at the provided resolutions for this project (multispectral imagery: 0.16 to 0.5 m spatial resolution; LiDAR: 1 m horizontal resolution). It may be possible to detect very young trees or shrubs in spring before the start of the growing season when grass and herbaceous cover have not yet been established. However, to assess the health of the vegetation, multispectral indices during the summer months are required. This would necessitate remote sensing data to have been collected twice within a single year during specific timeframes, which may not have occurred, or which may lead to significantly higher costs.

The use of drones might be another alternative to acquire VHR imagery by flying at low altitude. The spatial resolution of drone-based LiDAR systems can be much higher and point clouds of 100 pts/m^2 or larger can often allow differentiation of small woody vegetation from grasses and other herbaceous species. In fact, seedling detection tools on seismic lines are being developed by the Boreal Ecosystem Recovery and Assessment Project (BERA[3]). However, current Canadian regulations restrict drone operations to within visual line-of-sight (VLOS), which would still require drone operators go to the wellsites in person, reducing the value of using remote sensing approaches. Exceptions for beyond visual line-of-sight (BVLOS) flights require a Special Flight Operations Certificate (SFOC). Recognizing the limitations this imposes for a variety of remote sensing applications; Transport Canada has proposed new regulations to facilitate routine BVLOS operations. These proposed amendments aim to allow drones weighing up to 150 kg to operate BVLOS in sparsely populated areas, at low altitudes, and in uncontrolled airspace without the need for an SFOC[4]. These changes could greatly support large-scale forest reclamation efforts by flying drones at low altitudes over large areas without the need for the drone operator to travel to each wellsite.

While these challenges are primarily technical, we believe they will be overcome in the near future. As remote sensing data resolution improves both spatially and temporally, addressing these challenges will become easier. For example, spaceborne narrow-band, VHR hyperspectral imagery may become more readily available in the future, which could help address this problem.

[3] http://beraproject.org/
[4] https://gazette.gc.ca/rp-pr/p1/2023/2023-06-24/html/reg6-eng.html

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Furthermore, machine learning (ML) algorithms and artificial intelligence (AI) approaches for classification tasks will continue to improve, likely at a very fast pace which may help address these challenges. For example, Janga et al. (2023) report that recent developments in deep learning and neural networks have significantly enhanced the accuracy and efficiency of classification tasks, such as image classification, land cover mapping, and object detection. These improvements are driven by the increasing availability of large datasets and the continuous evolution of computational power. Additionally, the integration of AI with remote sensing technologies has led to more sophisticated models capable of handling complex and high-dimensional data. As research in this area progresses, it is expected that AI and ML algorithms will continue to evolve at a rapid pace, further improving their performance and expanding their applications in various domains. We expect these advances to enable automated approaches to a portion of these assessments. More specifically, there is ongoing research on using airborne remote sensing imagery and convolutional neural networks to detect tree seedlings on seismic lines (Byford et al., 2023). This research is particularly relevant for reclamation certification, as it addresses the risks of missing woody vegetation on recently reclaimed wellsites, as highlighted in this document.

Currently, the greatest value of remote sensing technologies lies in supporting, rather than replacing, the in-field assessment process, particularly for sites where LiDAR data were collected 5 to 7 years after reclamation (or post-abandonment, in the case of natural regeneration). This is especially relevant for the approximately 172,000 abandoned wellsites in Alberta that require reclamation certification. A multi-temporal approach using publicly available multispectral imagery from Sentinel-1, Sentinel-2, and Landsat can be effectively employed to develop a decision framework for classifying sites into 'pass', 'uncertain', and 'fail' categories, as demonstrated by one of the consultants in this study. This workflow is scalable and enables batch processing of large numbers of sites, distinguishing clear passes from uncertain or failed cases. Such pre-screening improves efficiency by helping prioritize financial and human resources where they are most needed.

This project has also highlighted that the approaches currently used by those completing assessments vary in their methodologies and outcomes. This variability may create initial challenges in ensuring acceptance by regulators and will require leveraging non-standard application processes. As indicated, consultants would benefit from high transparency in the tools and approaches they use to determine reclamation assessment outcomes. Additionally, we expect these approaches to become more standardized over time as the most efficient, cost-effective, and reliable methods are likely to be widely adopted. In the meantime, these approaches can still provide valuable cost and effort savings while delivering reliable outcomes for a portion of the reclamation assessment process.

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An alternative strategy involves establishing a library of field-validated remote sensing test datasets with known reclamation outcomes. These datasets could serve as standardized benchmarks for evaluating the accuracy and robustness of classification models developed by remote sensing practitioners. This approach supports ongoing innovation while ensuring compliance with regulatory requirements. The Open Data Areas Alberta Project[5] could be leveraged to further develop this strategy. This dataset provides information on earth observation, remote sensing, geospatial data, environmental data, and social and economic datasets from private industry and government for six key areas in Alberta (Beaver Hills, Fort McMurray, Fox Creek, RMH Sylvan, Taber, Utikuma Lake).

While the guidance in this document primarily draws from remote sensing assessments of wellsites within Forested Lands, many of the challenges identified, particularly related to LiDAR, may not apply to Grasslands and Cultivated Lands. In forested environments, LiDAR is valuable because it provides detailed information on vegetation structure, including canopy height, density, and woody vegetation abundance, key indicators of forest recovery. However, in non-forested settings such as grasslands and cultivated lands, these structural metrics are less critical and LiDAR may not be necessary. Due to the relative homogeneity of these landscapes, consistently available open-source remote sensing data with medium spatial resolution, such as Landsat, Sentinel-1, and Sentinel-2, can be sufficient for assessing vegetation cover, productivity, and land use change over time. However, the identification of undesirable or noxious weed species would still require field visits under the current regulatory framework.

[5] https://opendataareas.ca/

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