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# Assessment of Remote Sensing Technologies for Regional Reclamation Monitoring in Alberta

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# 1 Introduction

Throughout Canada, areas occupied by wetlands fulfil vital functions related to clean water, carbon sequestration, biodiversity and flood protection. However, anthropogenic activities and climate change increasingly pose threats to vulnerable wetland ecosystems. The construction of wellsites, pipelines, access roads and related infrastructure in support of resource exploitation has generated disturbed land fragments throughout large remote areas. This increases potential risk factors, such as soil erosion, the restriction of wildlife mobility, the decline of native species and the loss or contamination of water resources, which threaten the integrity of vulnerable ecosystems.

Recognizing the importance of mitigating the impact of land disturbance, the Alberta *Environmental Protection Act*[1] (*EPEA*) and Conservation and Reclamation Regulation[2] requires operators of specified lands to conserve, reclaim, and obtain a reclamation certificate. Following a disturbance, these areas must be reclaimed to meet an equivalent land capability; or:

*the ability of the land to support various land uses after conservation and reclamation is similar to the ability that existed prior to an activity being conducted on the land, but that the individual land uses will not necessarily be identical (http://www.qp.alberta.ca/documents/Regs/1993_115.pdf).*

However, practice and technology developments for both reclamation in peatlands and the assessment of reclamation success are in early stages. Therefore, considerable uncertainty remains in both achieving and measuring reclamation success. Measuring reclamation success requires regular monitoring, which enables:

- problems to be identified at early stages;
- comparisons between different reclamation practices; and,
- assessments of if/when equivalent land capability has been achieved.

Executing the required monitoring assessment using conventional, field-based methods is cost and labour intensive and may be ineffective for remote, inaccessible sites. Remote sensing technologies offer the potential to overcome this limitation by providing cost-effective observations of large areas at a high spatial resolution and frequency.

This study was executed with the objective to assess the contribution of remote sensing to monitoring at site level in Alberta. To this end, the technical maturity of airborne and satellite-based remote sensing technologies was assessed with respect to their ability to address individual reclamation criteria for peatlands. Section 2 provides a brief overview of applicable remote technologies. Section 3 presents the approach adopted for the technology assessment. The results of the analysis are presented in Section 4, while Section 5 describes recommendations for future implementation.

[1] http://www.qp.alberta.ca/documents/acts/e12.pdf
[2] http://www.qp.alberta.ca/documents/Regs/1993_115.pdf

## 2 Remote Sensing Technologies for Reclamation Assessment

The discipline of remote sensing is concerned with the gathering of information about targets of interest from a distance. This is achieved by measuring the amount of electromagnetic energy emanating from those targets. Remote sensing systems are broadly classified into passive and active sensors. Passive sensors register the amount of solar radiation reflected or thermal radiation emitted by the Earth's surface and therefore rely on an external source of illumination. Conversely, active sensors provide their own illumination by generating and emitting electromagnetic energy and measuring the proportion of that energy reflected by the targets of interest.

The utility of remote sensing systems for a particular application is determined by their respective spatial resolution, revisit frequency and spectral configuration. Spatial resolution determines the amount of detail that can be captured by the sensor. It is expressed as the size of a picture element (pixel) in ground distance units (e.g. meters). Today's operational remote sensing systems deliver data at resolutions ranging from less than 1 m to more than 1 km. The revisit frequency of the sensor is defined as the time interval between the successive imaging of the same geographic area. The spectral configuration of a sensor includes the number of spectral bands as well as their positioning in the electromagnetic spectrum and their respective sensitivity. Another important consideration is the swath coverage, indicating the area on the ground covered by a single image, or scene.

While similar remote sensing technologies can be deployed on aircraft and satellites, the choice of platform has implications for coverage, spatial resolution and revisit frequency. Airborne remote sensing use sensors deployed primarily on fixed-wing aircraft, although helicopter and aerostats have been used as remote sensing platforms. More recently, unmanned airborne vehicles (UAVs) have been used more, particularly in the developing context of beyond-visible-line-of-sight. For many decades, aerial photography has been used as the primary remote sensing technology for a wide range of applications, such as topographic mapping, forest inventories, land cover mapping and geological mapping. Today, airborne image acquisitions rely on a wide range of digital camera systems. Airborne remote sensing provides flexible, on-demand coverage at a spatial resolution in the centimeter or decimeter range. The swath covered by individual flight lines is typically hundreds of meters wide.

Satellites operate on a fixed orbit, providing systematic repeat coverage of most of the earth's surface. Satellite-borne remote sensing systems have been providing remotely sensed imagery for more than four decades, and recent years have seen a drastic increase in data availability, quality and access by end-users. Remote sensing is particularly useful for the monitoring of extensive, remote and isolated geographic regions that do not lend themselves easily to conventional, field-based data collection. The spatial resolution of satellite-based sensors applicable to reclamation monitoring ranges from 50 centimeters to 10 meters. The corresponding swath widths for individual satellite images ranges from less than 15 km to more than 250 km. Satellite remote sensing missions are often operated as constellations of two or more satellites, resulting in effective revisit frequencies of several days.

## 2.1 Optical Sensors

For this investigation, emphasis was placed on optical sensors, including panchromatic, multispectral and hyperspectral systems. As passive sensors, optical instruments register electromagnetic radiation reflected by the Earth's surface at visible (~0.4 to 0.7 µm), near-infrared (NIR, ~0.7 to 1.5 µm) and shortwave-infrared (SWIR, ~1.5 to 2.5 µm) wavelengths. Panchromatic sensors comprise a single, wide spectral band across visible and NIR wavelengths. Multispectral sensors, by contrast, use several distinct spectral bands in the visible, NIR and SWIR wavelength intervals. This makes it possible to employ the specific reflection and absorption characteristics of any target features (e.g. vegetation, minerals) and increase the amount of information obtained for these types of targets. Hyperspectral sensors provide a much higher spectral resolution, using many (up to hundreds) spectral bands with a narrow bandwidth (~10 nm) in an effort to characterize a detailed spectral response of a wide range of surface features. Optical imagery is used in applications such as coastal habitat mapping, extraction of shallow water bathymetry and water quality monitoring.

## 2.2 Synthetic Aperture Radar

In addition to optical sensors described above, satellite radar sensors were considered in this investigation due to their specialized sensitivities to moisture variations and ground motion. Radar systems operate in the microwave spectrum, are largely weather-independent, can acquire images day and night and are available on airborne and satellite platforms. Radar backscatter signal depends on the parameters of the imaged surface such as target material and conductivity and system characteristics, such as wavelength, incidence angle and polarization. Radars use an antenna to emit and collect the microwave signal and spatial resolution improves as the length of the antenna increases.

Due to the large antenna size, side-looking airborne radar (SLAR) is restricted to aerial platforms, typically fixed-wing planes. By contrast, synthetic aperture radar (SAR) uses the forward motion of the sensor platform, while taking into account Doppler shift of the collected signal to synthetically increase antenna aperture. Although SAR sensors can be flown on aircraft and satellites, all imaging satellite radars are SAR sensors. In the context of this study, only satellite-based SAR sensors are considered. Most current radars operate in C-Band (wavelength ~5 cm) or X-Band (wavelength ~3 cm), although L-band (15 to 30 cm) and P-Band (30 to 100 cm) systems have been used on airborne and satellite platforms. Radars can be configured to transmit and receive horizontally or vertically polarized radiation.

Appendix A provides a summary of the characteristics of representative satellite remote sensing systems for reclamation monitoring.

# 3 Approach

This analysis considered the reclamation criteria for peatlands as described in AEP (2017). In addition, reclamation criteria as outlined in ESRD (2013) were used to account for complex, stratified sites. A complete list of parameters forming the requirements baseline for this study is presented in Table 1 and Table 2.

Table 1: Reclamation Criteria for Peatlands (AEP, 2015)

| Reclamation Criteria for Peatlands | |
|---|---|
| Landscape Assessment | Moisture Regime |
| | Open Water/Ponding - Water |
| | Open Water/Ponding – Submerged Vegetation |
| | Open Water/Ponding – Surrounding Vegetation |
| | Offsite Drainage |
| | Riparian Areas Bank and Shore Stability |
| | Water Erosion – Gullying |
| | Water Erosion – Rilling pedestaling, fans |
| | Wind Erosion |
| | Bare Areas |
| | Gravel and Rock |
| | Industrial Debris |
| Vegetation Assessment | Desirable Species |
| | Desirable Species – Vegetation Type |
| | Undesirable Species Cover |
| | Undesirable Species Cover – Vegetation Type |
| | Species Richness |
| | Woody Species |
| | Woody Species – Vegetation Type |

Table 2: Reclamation Criteria for Forested Lands (ESRD, 2013)

| Reclamation Criteria for Forested Lands | |
|---|---|
| Landscape Assessment | Drainage – Surface Water Flow (Onsite/Offsite) |
| | Drainage – Ponding |
| | Riparian Functions - Bank or Shore Stability |
| | Water Erosion – Gullying |
| | Water Erosion – Rilling pedestaling, fans |
| | Wind Erosion |
| | Soil Stability – Slumping/Wasting |
| | Soil Stability - Subsidence |
| | Bare Areas |
| | Operability – Micro-Contour |
| | Operability – Meso- and Macro-Contour |
| | Operability - Gravel and Rock |
| | Debris – Woody Debris |
| | Debris - Industrial and Domestic Refuse |
| Soil Assessment | Soil Disturbance |
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| | Vertical Processes – Rooting Restrictions |
| | Level 2 Soil Assessment |
| Vegetation Assessment | Desired Plants – Woody Species |
| | Desired Plants – Herbaceous Species |
| | Quantity - Production |
| | Quality – Plant Growth, Development |
| | Quality – Limitations Affecting Vegetation |
| | Weeds/Undesirable Plants |
| | Litter and LFH |

Remote sensing systems evaluated in this investigation included panchromatic (PAN), multispectral (MS), hyperspectral (HS) and synthetic aperture radar (SAR) sensors. PAN and MS sensors were evaluated for both airborne and satellite platforms. Since satellite HS imagery is currently not available on an operational basis, only airborne HS data was considered in this investigation. By contrast, only satellite-based SAR imagery was included in this study as satellite SAR covers large areas data is widely accessible. Table 3 presents a summary of platforms, sensors and the corresponding nominal spatial resolutions considered for this investigation is presented in Table 3.

The technical maturity of the sensors described above and the corresponding methods to extract information relevant to reclamation monitoring was assessed using technology readiness levels (TRL) presented in Table 4. This TRL classification has been specifically adapted for the use of satellite imagery within the oil and gas sector (Puestow et al., 2015). For each of the parameters in the requirements baseline, the utility of remote sensing technologies was assessed using the expected performance levels described in Table 5.

The approaches to information extraction considered in this evaluation included visual interpretation and semi-automated classification for PAN, MS and HS data, as well as change detection for time series of imagery. For SAR data, specialized processing applies to the derivation of soil moisture variations and ground motion. Where available, the analysis considered relevant work focused on the use of remote sensing for reclamation in Alberta (e.g. Ireland et al., 2017). However, since methodologies utilizing remote sensing are not yet fully integrated into reclamation procedures, this investigation relied on established methods for related activities such as the generation of forest inventories, land cover mapping and crop monitoring.

Table 3: Remote Sensing Platforms and Sensors Considered in the Analysis

| Platform | Sensor | Nominal Spatial Resolution |
|---|---|---|
| Airborne | Panchromatic (PAN) | < 50 cm |
| | Multispectral (MS) | < 50 cm |
| | Hyperspectral (HS) | 2 to 5 m |
| Satellite | Panchromatic (PAN) | < 1 m |
| | Multispectral (MS) | 1 to 10 m |
| | Synthetic Aperture Radar (SAR) | 1 to 10 m |

Table 4: Technology Readiness Levels for Remote Sensing Products and Services (Puestow et al., 2015)

| | TRL | Development Stage Completed | Definition of Development Stage |
|---|---|---|---|
| Concept | 0 | **Hypothetical Concept**<br>(Basic R&D, paper concept) | Basic scientific/engineering principles observed and reported in peer-reviewed literature; paper concept; no analysis or testing completed; no design history. |
| Proof-of-Concept | 1 | **Proven Concept**<br>(Based on applied research) | Product/service concept formulated; concept and functionality proven by analysis or reference to features common with/to existing technology; no design history; essentially a paper study based on |

| | TRL | Development Stage Completed | Definition of Development Stage |
|---|---|---|---|
| | | | applied research; conceptual rather than actual processes or products. |
| | **2** | **Validated Concept** (Experimental proof of concept and limited validation against reference data) | Product/service concept (or novel features of existing products/services) is evaluated using a limited amount of reference data; draft of the service/process chain generates preliminary products; evaluation of input EO and non-EO data availability and quality is performed; key elements documented in peer-reviewed literature. |
| **Prototype** | **3** | **Prototype Tested** (Function, performance and reliability of critical service components tested) | Prototype of critical service components is built and put through (generic) functional and performance tests; reliability tests are performed including input data access, process chain, product generation and turn-around time (esp. for NRT applications); the extent to which user requirements are met are assessed and potential benefits and risks are demonstrated. |
| | **4** | **Service Tested** (Pre-operational service demonstration) | Meets all requirements of TRL 3; designed and built as pre-operational service chain but not fully implemented or integrated with user processes; testing of prototype function against performance criteria in the intended operational setting. |
| | **5** | **Service Demonstrated** (Operational service demonstration) | Meets all the requirements of TRL 4; designed and built as operational service; integration of service products into user processes demonstrated, incl. interfaces to user processes, output formats and delivery mechanisms; meets some user requirements in terms of information content, reliability and accuracy. |
| **Field Qualified** | **6** | **Service Implemented** (Service is fully implemented and validated; partially meets user requirements) | Meets all the requirements of TRL 5; operational end-to end service implemented; interfaces for integration into user processes established and tested; partially meets user requirements in terms of information content, reliability and accuracy. |
| | **7** | **Field Proven** (Service is accepted as proven technology; operated > 3 years; fully meets user requirements) | EO-based product/service is firmly integrated into user processes; operating for more than three years; fully meets user requirements in terms of information content, reliability and accuracy. |

Table 5: Performance levels for monitoring and assessments of disturbances and reclaimed areas

| **Increasing Certainty ➔** | | |
|---|---|---|
| Not Applicable | Potentially Applicable | Applicable |
| | TRL 0 to 4 | TRL 5 to 7 |
| Cannot meet the requirements | Only partial validation may have taken place, but the technology has not been comprehensively validated | Proven and fully validated. Performance and limitations are well understood |

# 4 Contribution of Remote Sensing to Reclamation Assessments

The following sections provide the result of the analysis of remote sensing applicable to the assessment of wellsite reclamation for peatlands and forested areas.

## 4.1 Peatlands

The result of the qualitative evaluation of remote sensing for the reclamation of peatland areas is presented in Table 6 and Table 7.

The moisture regime is largely indicated by variations in topography and drainage pattern at the micro- and macro-contour scales. While information at the micro-scale level is difficult to obtain from imagery, airborne PAN and MS data are well suited to providing topographic and drainage information at the macro-scale.

For unvegetated or sparsely vegetated areas, time series of satellite SAR imagery can provide spatio-temporal information on the variability of soil moisture, which may indicate condition suitable for peatland reclamation. Ponding water on sites can be extracted reliably from optical airborne or satellite imagery, especially if a NIR channel is present.

Submerged vegetation can be mapped with MS and HS imagery. Depending on the applicable local scale and spatial extent of the aquatic vegetation, aerial or satellite-based imagery may be used. For vegetation surrounding ponds, airborne PAN or MS data are preferred due to the greater spatial resolution. Indicators of offsite drainage can be derived from airborne PAN and MS imagery.

The ability to characterize riparian areas as well as bank and shoreline stability depends directly on the spatial scale and level of thematic detail required. The presence of riparian vegetation is readily identified using PAN and MS imagery, but evaluating species composition and successional trajectories will likely require in-situ observations. Specific spectral response pattern of individual plant species may be exploit using HS imagery.

Evidence of water erosion can be readily extracted from airborne PAN and MS data. Depending on the size and extent of erosion features, satellite PAN imagery may be applicable as well. Scale is also important for characterizing any impacts of wind erosion. For features such as micro-scale pedestalling or deflation, direct observations may not be possible using airborne or satellite imagery. However, adverse effects on plant health may be detectable using time series of MS and HS imagery.

Bare areas, as well as patches of gravel and rock can be readily mapped with PAN, MS and HS imagery within the limitations of sensor spatial resolution. For industrial debris, a higher spatial resolution is preferred. In some cases, satellite SAR may be useful in identifying the presence of metal structures due to the characteristic backscatter of metal targets in the microwave spectrum.

Regarding vegetation assessment parameters, remotely sensed imagery is not adequate for providing differentiated information compatible with 1m and 10m plots. However, airborne and satellite HS and MS data can be useful is extracting basic vegetation categories, such as bryophytes, herbaceous and woody vegetation. For woody vegetation, species identification is operational using airborne PAN and MS imagery. The information collected during in-situ surveys can be used to train classification algorithms operating on MS and HS data to extract species information, which may be useful for site assessments in inaccessible areas and/or undisturbed assessments.

Table 6: Expected Performance of Remote Sensing for Landscape Assessment of Peatlands

| Landscape Assessment Parameters | Airborne Platform | | | Satellite Platform | | |
|---|---|---|---|---|---|---|
| | PAN | MS | HS | PAN | MS | SAR |
| Moisture Regime | | | | | | |
| Open Water/Ponding - Water | | | | | | |
| Open Water/Ponding – Submerged Vegetation | | | | | | |
| Open Water/Ponding – Surrounding Vegetation | | | | | | |
| Offsite Drainage | | | | | | |
| Riparian Areas Bank and Shore Stability | | | | | | |
| Water Erosion – Gullying | | | | | | |
| Water Erosion – Rilling pedestaling, fans | | | | | | |
| Wind Erosion | | | | | | |
| Bare Areas | | | | | | |
| Gravel and Rock | | | | | | |
| Industrial Debris | | | | | | |

Table 7: Expected Performance of Remote Sensing for Vegetation Assessment of Peatlands

| Vegetation Assessment Parameters | Airborne Platform | | | Satellite Platform | | |
|---|---|---|---|---|---|---|
| | PAN | MS | HS | PAN | MS | SAR |
| Desirable Species | | | | | | |
| Desirable Species – Vegetation Type | | | | | | |
| Undesirable Species Cover | | | | | | |
| Undesirable Species Cover – Vegetation Type | | | | | | |
| Species Richness | | | | | | |
| Woody Species | | | | | | |
| Woody Species – Vegetation Type | | | | | | |

## 4.2 Forested Areas

Table 8 to Table 10 summarize the results of the evaluation for reclamation criteria applicable to forested areas. For parameters related to drainage, riparian functions, erosion and debris the utility of remote is the same as for peatland areas. Depending on the size of the features, indicators of soil stability can be extracted from airborne (PAN, MS) and satellite PAN imagery. Under certain conditions, the amount of soil subsidence can be mapped and quantified using time series of satellite SAR imagery. This is applicable only for unvegetated or sparsely vegetated sites. While remote sensing offers limited potential to characterize topography at the micro-scale, macro-and meso-scale contours can be extracted from airborne and satellite data.

In the case of the assessment of soil properties, the potential of remote sensing is restricted to the mapping of spatial and temporal patterns of soil disturbance. A limited amount of information about soil texture may be obtained, but that information will be limited to the soil surface visible to the sensor. Likewise, some indicators of rooting restrictions may be obtained from imagery, such as pooling water, evidence of vehicle tracks and vegetation health.

In the case of forested lands, desirable woody species can be identified with the aid of airborne imagery. Similarly, the principal quantity and quality parameters (spatial distribution and cover of desirable species, indicators of vegetation health) can be extracted using airborne PAN and MS sensors. HS imagery can be used to map undesirable species with specific spectral response patterns. Remote sensing is not applicable to the characterization of topsoil horizons and litter.

Table 8: Expected Performance of Remote Sensing for Landscape Assessment of Forested Lands

| Landscape Assessment Parameters | Airborne Platform | | | Satellite Platform | | |
|---|---|---|---|---|---|---|
| | PAN | MS | HS | PAN | MS | SAR |
| Drainage – Surface Water Flow (Onsite/Offsite) | Green | Green | Yellow | Yellow | Yellow | Red |
| Drainage – Ponding | Green | Green | Green | Green | Green | Yellow |
| Riparian Functions - Bank or Shore Stability | Yellow | Yellow | Yellow | Yellow | Yellow | Yellow |
| Water Erosion – Gullying | Green | Green | Yellow | Green | Yellow | Red |
| Water Erosion – Rilling pedestaling, fans | Green | Green | Yellow | Green | Yellow | Red |
| Wind Erosion | Yellow | Yellow | Yellow | Yellow | Yellow | Red |
| Soil Stability – Slumping/Wasting | Green | Green | Yellow | Green | Yellow | Yellow |
| Soil Stability - Subsidence | Yellow | Yellow | Red | Yellow | Yellow | Green |
| Bare Areas | Green | Green | Green | Green | Green | Yellow |
| Operability – Micro-Contour | Yellow | Red | Red | Yellow | Red | Red |
| Operability – Meso- and Macro-Contour | Green | Green | Green | Green | Green | Yellow |
| Operability - Gravel and Rock | Green | Green | Green | Green | Green | Yellow |
| Debris – Woody Debris | Yellow | Yellow | Yellow | Yellow | Yellow | Red |
| Debris - Industrial and Domestic Refuse | Green | Green | Yellow | Green | Yellow | Yellow |

Table 9: Expected Performance of Remote Sensing for Soil Assessment of Forested Lands

| Soil Assessment Parameters | Airborne Platform | | | Satellite Platform | | |
|---|---|---|---|---|---|---|
| | PAN | MS | HS | PAN | MS | SAR |
| Soil Disturbance | Green | Green | Green | Green | Green | Yellow |
| Surface Characteristics | Red | Red | Red | Red | Red | Red |
| Vertical Processes – Soil Texture | Red | Yellow | Yellow | Red | Yellow | Yellow |
| Vertical Processes – Consistence and Structure | Red | Red | Red | Red | Red | Red |
| Vertical Processes – Rooting Restrictions | Yellow | Yellow | Yellow | Yellow | Yellow | Yellow |
| Level 2 Soil Assessment | Red | Red | Red | Red | Red | Red |

Table 10: Expected Performance of Remote Sensing for Vegetation Assessment of Forested Lands

| Vegetation Assessment Parameters | Airborne Platform | | | Satellite Platform | | |
|---|---|---|---|---|---|---|
| | PAN | MS | HS | PAN | MS | SAR |
| Desired Plants – Woody Species | Green | Green | Green | Yellow | Yellow | Red |
| Desired Plants – Herbaceous Species | Red | Red | Yellow | Red | Red | Red |
| Quantity - Production | Green | Green | Yellow | Yellow | Yellow | Red |
| Quality – Plant Growth, Development | Yellow | Green | Green | Yellow | Green | Red |
| Quality – Limitations Affecting Vegetation | Yellow | Green | Green | Yellow | Green | Red |
| Weeds/Undesirable Plants | Red | Yellow | Green | Red | Yellow | Red |
| Litter and LFH | Red | Red | Red | Red | Red | Red |

# 5 Conclusions and Recommendations

This study was carried out to evaluate the contribution of airborne satellite remote sensing technologies to reclamation monitoring and assessment in Alberta. Using a requirements baseline of documented reclamation criteria for peatlands and forested lands, a qualitative evaluation was completed to assess the utility of airborne and satellite sensors for reclamation monitoring. Sensors under consideration included panchromatic (PAN), multispectral (MS), hyperspectral (HS) and synthetic aperture radar (SAR) systems. Since methodologies utilizing remote sensing are not yet fully integrated into reclamation procedures, the utility of remote technologies was assessed using related activities such as the generation of forest inventories, land cover mapping and crop monitoring.

The results of this investigation show that remote sensing is an effective way of obtaining relevant information for several reclamation parameters. Regarding vegetation assessments, the ability of remote sensing systems to differentiate between different bryophyte or herbaceous species to a level compatible with in-situ surveys is not yet fully developed. Of all sensors considered in this study, HS imagery has the highest potential for species identification, but more research is required to quantify performance levels for peatland reclamation. By contrast, the identification of woody species using airborne imagery is well established, particularly for forest inventories. These methods can be easily transitioned to the peatland reclamation context.

For unvegetated or sparsely vegetated sites, satellite SAR imagery has the potential for providing information about spatial and temporal soil moisture variations and ground motion, especially subsidence. This can be relevant in the early stages of the reclamation process to decide which sites have the soil, drainage and topographic conditions conducive to the forming of peatlands.

Including remote sensing in the portfolio of assessment methods will likely increase the cost-effectiveness of monitoring and assessment processes. Given that remote sensing allows the systematic acquisition of information over large areas at lower spatial resolutions compared to in-situ methods, the largest impact of remote methods are expected for assessments at the landscape scale. In most cases, the sub-meter spatial resolution afforded by airborne sensors is required. However, satellite sensors with a spatial resolution as low as 10 m may be useful in quickly scanning thousands of square-kilometers for significant changes in surface cover or vegetation health over areas containing many reclamation sites.

Remote sensing can be incorporated into operational reclamation monitoring and assessment workflows within a spatially hierarchical framework. In this case, freely available, systematically acquired satellite imagery would be used to analyze large areas comprising thousands of square-kilometers for significant changes in surface cover or vegetation over reclamation sites. This information would be used to target the acquisition of airborne or satellite imagery over areas of concern. If the high-resolution acquisitions do not provide all information that is required, field personnel can be deployed on those sites that required in-situ observations. The hierarchical, multi-resolution approach to reclamation monitoring and assessment will be particularly cost-effective for large numbers of sites located in remote, inaccessible areas.

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