ALBERTA RECLAMATION CERTIFICATION – DIGITAL TECHNOLOGY ASSESSMENT

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October 28, 2022

EXECUTIVE SUMMARY

Earth observation (EO), remote sensing (RS), and other digital technologies are emerging as powerful tools for monitoring the environment and collecting environmental data. These technologies can be used to monitor vegetation, landscape features, soil, water bodies, and wetlands. Used in combination with ground-based data collection they can support reclamation assessment and compliance evaluation. Remote sensing technologies have been used in numerous studies across the globe to monitor reclamation success and have been similarly implemented in several jurisdictions. Recently drafted *Alberta Directives for Reclamation Certification Site Assessment for Pits and Quarries in Cultivated and Forested Lands* enable the use of new technology-based data collection to augment in-field assessments. Given the advances in EO/RS and digital technologies made in recent years, there is an opportunity to utilize these technologies in reclamation certification assessments in Alberta.

This report represents two related objectives. The first was to evaluate the applicability of EO, RS, and digital technologies for the collection of environmental data relevant to Alberta Reclamation Certification Site Assessment criteria. This report evaluates the evidence to support use of remote-sensed data to augment in-field assessments, considering especially assessments of accuracy and precision. The second objective was to determine if and how other jurisdictions have applied RS, EO, and other digital technologies to the regulation and enforcement of environmental policies related to reclamation. By examining relevant regulations, guidance documents, and government information sources, this report presents cases where these technologies have been applied by governments in Canada, Australia, and the United States of America to reclamation monitoring and assessment and similar environmental purposes.

There are numerous sensors and platforms for remote sensing and digital technologies, each with advantages and disadvantages. Sensors may be passive or active, with active sensors being less sensitive to obstruction by cloud cover. Passive sensors may be optical (i.e., panchromatic, multispectral, hyperspectral, RGB cameras) or thermal. Active sensors include technologies such as synthetic aperture radar (SAR) and light detection and ranging (LiDAR). Platforms may be spaceborne, airborne, drone-based, or ground-based (i.e., mounted on vehicles). Combining multiple sensors can provide greater accuracy.

EO/RS have been used to assess land use and cover most frequently. With optical sensors it is possible to study vegetation form, health, biomass, and species composition. Technologies such as SAR and LiDAR enable the collection of detailed information regarding canopy structure and density. It is possible to study both overstory and understory plant species using appropriate sensors and platforms. Topography, elevation, and slope are mostly commonly assessed with LiDAR and interferometric SAR (InSAR). Soil properties can be assessed with optical and microwave sensors, although typically the sensors have a coarse resolution. Ground-based sensors, such as proximal soil sensors, may be more appropriate for reclamation sites in Alberta. Water bodies and wetlands are also commonly monitored with remote sensing technologies. When considering cultivated land, additional sensors (such as variable rate sensors) may be available that are not applicable to forested land. Authors typically reported good or moderate accuracy for digital technologies compared to in-field measurements, but accuracy varies depending on the site conditions, sensor, and platform.

When considering whether a particular sensor and platform are appropriate for Alberta reclamation assessment criteria on forested and cultivated lands, the spatial resolution, revisit frequency, and spectral configuration of the sensor and platform must be considered. For example, some technologies may only be operationally available at scales much larger than a reclamation site. In this report, remote sensing and

digital technologies were evaluated against specific reclamation assessment criteria. The literature review revealed numerous applications of digital technologies that are directly applicable to reclamation criteria and monitoring in Alberta. Digital technologies have the potential to be used to supplement in-field data collection, however it should be noted that in most cases, the application of digital technologies will require in-field data collection as validation. There are opportunities to capitalize of the recent advances in remote sensing and digital technologies to enhance the reclamation certification process in Alberta.

Use of EO, RS, and digital technologies in an enforcement capacity is most common in Australia, although there is some usage in Canada and the United States of America. Generally, this enforcement is not specifically in the field of reclamation, but with regards to illegal activities on public lands (such as illegal vegetation removal). Use of these technologies is promoted in each country for reclamation monitoring, such as for vegetation cover and landform stability. Similarly, in other industries and sectors, such as forestry, the benefits of vegetation monitoring through RS, EO, and related digital technologies are also touted. Still, it is important to note that in all or nearly all cases, these technologies are paired with some degree of on-site ground truthing to verify accuracy of the data and related assumptions.

Many governments and research institutions are actively pursuing research projects that will further develop the use of RS, EO, and digital technologies, in order to improve the accuracy of data collected in this manner. Particular emphasis is being placed on developing standardized approaches that perform well in a variety of scenarios, such as standardized vegetation survey methods for a variety of ecosystems via unmanned aerial vehicles (UAVs), for example. There is ample opportunity to either benefit from these research projects, or participate in the development of a similar, standardized approach for Alberta.

The reviews completed indicate that there is opportunity for the use of EO, RS, and digital technologies to support reclamation assessment processes, and meet associated regulatory and compliance needs. In order to make use of these opportunities, additional validation must be completed to ensure that these technologies can be applied in a risk-managed approach.

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ACKNOWLEDGEMENTS

The jurisdictional review was completed by Vertex staff and reviewed by InnoTech Alberta researchers. The literature review was completed by InnoTech Alberta researchers with review by Vertex and others. The authors would like to thank all who assisted with finding and reviewing relevant papers and providing support including, but not limited to, Ryan Melnichuk and Marshall McKenzie (InnoTech Alberta) and Chris Powter (Enviro Q&A Services).

CITATION

Thacker, S., Venskaitis, S., Renkema, K., Herdman, E. 2022. Digital Technology Assessment for Reclamation Certification in Alberta. Report prepared for InnoTech Alberta, Edmonton, AB. 70 pp.

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GLOSSARY

Eddy covariance flux: An atmospheric measurement technique commonly used in meteorology, oceanography, hydrology, agriculture, and industry to estimate gas fluxes (i.e., carbon dioxide and methane), water vapour, momentum, and heat.

Endmember: Constituent spectra derived from a mixed pixel. In environmental monitoring, endmembers typically refer to parameter such as vegetation, soil, or water.

Hyperspectral sensor: An optical sensor that acquires data from hundreds to thousands of narrow bands of the electromagnetic spectrum.

Interferometric synthetic aperture radar (InSAR): Uses two SAR observations of the same area (taken from different positions) to extract distance information about the Earth's surface.

Light detection and ranging (LiDAR): Uses a pulsed laser to measure distances, or ranges, to the Earth. Combined with other system data, these light pulses provide 3D information about the Earth's shape and surface.

Multispectral sensor: An optical sensor that acquires data from a number of bands across visible, near infrared, and shortwave infrared wavelengths.

Panchromatic sensor: An optical sensor that acquires data from a single wide spectral band at visible and near infrared wavelengths.

Photogrammetric point clouds (PPC): Generated from densely overlapping photographs with software that uses photogrammetric methods; provide a very detailed model of the surface/object being studied.

Polarimetric interferometry SAR (PolInSAR): Combines polarimetric and interferometric information in SAR images.

Polarimetric synthetic-aperture radar (PolSAR): Uses multiple polarization combinations to determine scattering properties of the subject area, which can be used to obtain information about surface roughness and vegetation structural orientation.

Radio detection and ranging (radar): In this report, imaging radar is focused on, which provides light to an area or surface, typically using radio wavelengths, to obtain information about the Earth's surface.

RGB sensor: A sensor that utilizes red, green, and blue (RGB) bands of the electromagnetic spectrum (visible wavelengths).

Spectral un-mixing: Conversion of the spectral signature of a mixed pixel (i.e., pixel which contains two features/classifications but may be below the resolution of the sensor) into constituent spectra (endmembers) and corresponding fractions (abundances).

Stereoscopic imagery: Produced when a sensor acquires two images of the same area at different angles; often used to produce digital elevation models (DEMs).

Synthetic-aperture radar (SAR): A form of radar which uses radio wavelengths and microwave wavelengths of the electromagnetic spectrum.

PART 1: REVIEW OF DIGITAL TECHNOLOGY RESEARCH IN RELATION TO RECLAMATION CERTIFICATION

1.0 INTRODUCTION

1.1 Background Information and Project Objectives

Digital technologies are emerging as useful tools for monitoring the environment and detecting environmental change, by collecting data on parameters such as vegetation, landscape features, soil, water bodies, and wetlands. Recently drafted Alberta Directives for Reclamation Certification Site Assessment for Pits and Quarries in Cultivated and Forested Lands enable the use of technology-based data collection to augment in-field assessments. There is an opportunity to evaluate digital technologies to determine how they could be used to compliment or supplement the reclamation certification process in Alberta. In this report, we use digital technologies as an umbrella term for technology-based data collection. Digital technologies encompass earth observation (EO), remote sensing (RS), and other technologies such as ground-based or vehicle-mounted sensors and sensor networks used to monitor vegetation, soil, landscape, water, and air.

The objective of this report is to evaluate the applicability digital technologies for the collection of environmental data relevant to Alberta Reclamation Certification Site Assessment criteria. The report evaluates whether there is substantive evidence to support the use of remotely sensed data to augment in-field assessments. This report used both peer-reviewed and grey literature and considers: (i) the comparability of researched habitats to those found in Alberta forests and cultivated lands, and (ii) assessments of accuracy and precision.

The types of digital technologies evaluated include those indicated in Powter et al. (2016), as well as technologies described in the literature:
- Hyperspectral imagery
- Infrared imagery
- LiDAR (light detection and ranging)
- Multispectral imagery
- Panchromatic imagery
- Photogrammetry
- Proximal soil sensors
- Radar (radio detection and ranging)
- Reflectance spectroscopy
- Sensor networks
- Stereoscopic imagery
- Thermal imagery

Collection of data remotely is particularly useful for sites that are far from vehicle or foot access, or which do not allow for an aerial landing. Evaluation of reclamation criteria using remotely sensed data may allow for a reduction in the number or length of visits to perform on the ground assessments by identifying when a site is likely to pass reclamation criteria. Remote sensed data may also provide insight into on-site challenges that may prevent achievement of reclamation certification, allowing for early and efficient action, or may highlight areas of particular interest for focused assessment on larger sites. If evaluations of reclamation certification criteria using remote sensed data provide similar results to on the ground data collection in terms of accuracy and reliability, the use of remote sensing and digital technologies may be supported by policy to augment and eventually to replace some on the ground criteria assessment. This would reduce costs on a variety of sites, by reducing the number of samples collected and analyzed at a laboratory and/or decreasing on the ground assessment requirements.

The literature review assessed forested and agricultural systems, with an emphasis on reclaimed sites under both land uses. The findings are evaluated in terms of reclamation monitoring, vegetation, landscape features, soil, and water bodies and wetlands. The potential for remote sensing to be used to evaluate the specific reclamation criteria used in Alberta on cultivated and forested land is assessed.

1.2 Overview of Digital Technology Deployment

The concept of remote sensing can be traced back to the 1840s, when cameras secured to balloons were used to take photos of the Earth for topographic mapping (Graham, 1999). Satellite remote sensing began in the mid-1900s and the term "remote sensing" was first used in the United States in the 1950s (Graham, 1999). Since then, much work has been done to advance earth observation (EO), remote sensing (RS), and digital technologies.

These technologies can be used to monitor landscape features, vegetation, water bodies, and wetlands. Advanced, high spatial and spectral resolution sensors can be used to gain detailed information on a site and to enable additional derived data products through further analysis and extrapolation. As with most models, ground truthing is typically required to validate models developed from the sensor data. Advanced sensors are already deployed in the practice of precision agriculture and smart farming. EO/RS technologies are used in forestry for resource management. These same sensors are highly relevant to monitoring reclamation over time and assessing certification criteria, and are already used for these purposes in other jurisdictions (Chasmer et al., 2018; de Saavedra Alvarez et al., 2011; Karan et al., 2016; Lyu et al., 2020).

There has been much research on satellite-based multispectral imagery, but more recently hyperspectral imagery and LiDAR have become important technologies. Sensors are flexible in their deployment and can be affixed to a variety of platforms including aircraft (helicopters, planes), unmanned aerial vehicles (UAVs; i.e., drones), satellites, and can even be ground-based. Different deployments provide different costs and benefits, and the choice of sensor and platform depends on the specific application. Recent advances to improve the accuracy of measurements have been made, and may include combing multiple technologies such as thermal imagery, synthetic aperture radar (SAR), multispectral and hyperspectral sensors, and LiDAR (Chasmer et al., 2020; Lechner et al., 2020; Mitchell et al., 2017).

There have been many projects across Alberta evaluating the use of EO/RS for resource management and environmental monitoring, especially associated within oil and gas, mining, and the oil sands region (C-CORE, 2019; Chasmer et al., 2018; De Abreu et al., 2015; Quillévéré-Hamard et al., 2018; Rochdi et al., 2014). Pipeline spills, geohazards, and flaring can also be monitored via EO technology (De Abreu et al., 2015), in addition to a variety of vegetation and landscape parameters. While digital technologies are used for various environment-related projects in Alberta, the evaluation of soil characteristics is primarily conducted via in-field assessments.

In this report, we discuss available technologies and the application of remote sensing and digital technologies, focusing on how these technologies could support the reclamation certification process in Alberta.

1.3 Available Technologies

There are many different sensors and platforms available, and recent technological advances have greatly expanded the sensor and platform combinations possible and types of information that can be assessed.

1.3.1 Sensors

Sensors can be passive or active (Lechner et al., 2020). Passive sensors detect reflection of solar radiation, while active sensors send a signal and measure the return typically using laser or microwave signals (Hernandez-Santin et al., 2019). Active sensors such as LiDAR generate point cloud data used to create 3D images (Hamraz, Contreras, & Zhang, 2017). Most commonly, passive sensors measure radiation emitted by the sun and reflected or emitted by the Earth, and are used to classify and identify vegetation or landform features based on colour, texture, and structure (Hernandez-Santin et al., 2019).

Spectral data obtained from passive sensors can be used to develop vegetation indices for monitoring vegetation health and biomass overtime, as well as land cover classes; identify vegetation classes and species; evaluate drought stress; and assess soil properties. Passive sensors include optical and thermal sensors. Optical sensors are commonly used and acquire data within UV, visible wavelengths, and near-infrared wavelengths on the electromagnetic spectrum (Figure 1). Optical sensors may acquire data from a single wide spectral band at visible and near infrared wavelengths (panchromatic); a number of bands across visible, near infrared, and shortwave infrared wavelengths (multispectral); or from hundreds to thousands of narrow bands with very high spectral resolution (hyperspectral) (C-CORE, 2019; Lechner et al., 2020). Hyperspectral sensors typically “measure the reflected spectrum at wavelengths between 350 and 2,500 nm using 150–300 contiguous bands of 5- to 10-nm bandwidths” (He et al., 2011).

RGB cameras/sensors, which are also passive sensors, utilize red, green, and blue (RGB) bands of the electromagnetic spectrum (visible wavelengths). Using commercial grade cameras, 3D photogrammetric point clouds can be generated from densely overlapping photographs, often used to assess vegetation height; photogrammetry offers very detailed models of the object or surface being investigated, and the RBG data inherent to photogrammetric point clouds can be used to assess phenological changes (Hird et al., 2017b). Multispectral sensors have become more popular than RGB sensors in recent years (Ashapure et al., 2019), and multispectral and hyperspectral sensors tend to be the most commonly discussed in the literature today. Proximal soil sensors, reflectance spectroscopy, mobile sensors, fixed sensor networks, and camera traps constitute digital technologies that may be used in environmental monitoring; these technologies typically make use of passive sensors. Passive sensors cannot penetrate cloud cover or haze and cannot be used at night.

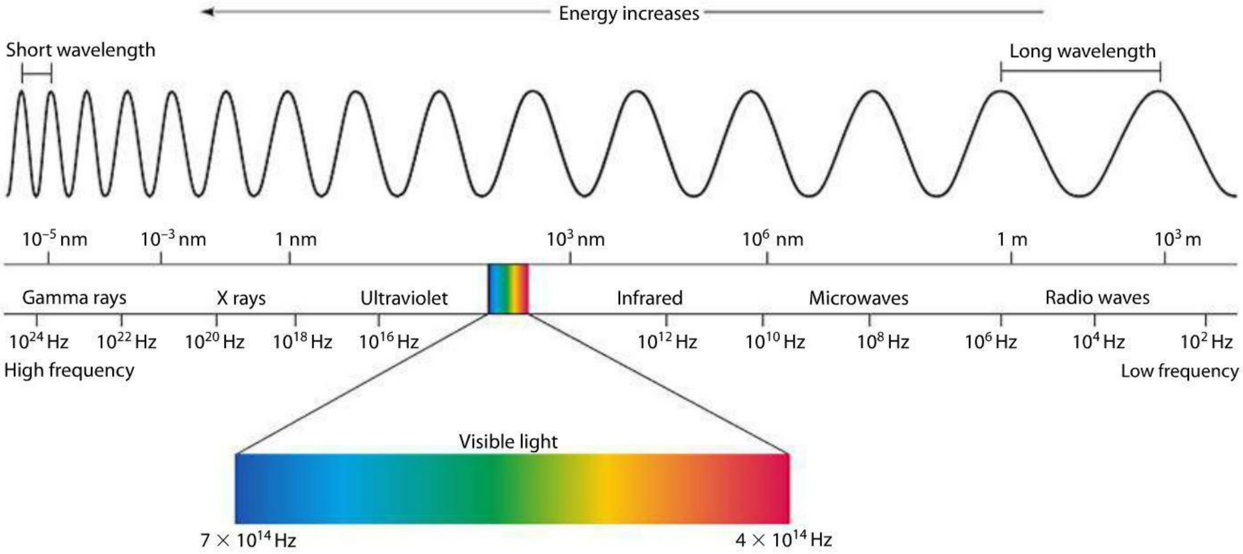

Figure 1. The electromagnetic spectrum.
Source: Mini Physics (2021)

Active sensors refer to technologies such as LiDAR (light detection and ranging) and radar (radio detection and ranging) utilize near-infrared wavelengths, microwaves, and radio waves depending on the specific technology. Active sensors are typically used to assess landscape features and soil properties, including soil moisture, and are also effective for assessing canopy height and cover. There are different forms of radar, including side-looking airborne radar (SLAR), synthetic aperture radar (SAR), interferometric SAR (InSAR), polarimetric SAR (PolSAR), and polarimetric interferometry SAR (PolInSAR). SLAR is restricted to aerial platforms due to antenna size, and therefore is less commonly used (C-CORE, 2019). Active sensors are not inhibited by cloud cover or darkness and can provide information on 3D structure, surface roughness, and water content. Active sensors have the ability to penetrate vegetation, forest canopy, and soil (Lechner et al., 2020), although there is variation in ability among sensors. For example, SAR may use bands of different wavelength and frequency (X, C, L, P bands) which have different penetration depths (Herndon et al. (2020)).

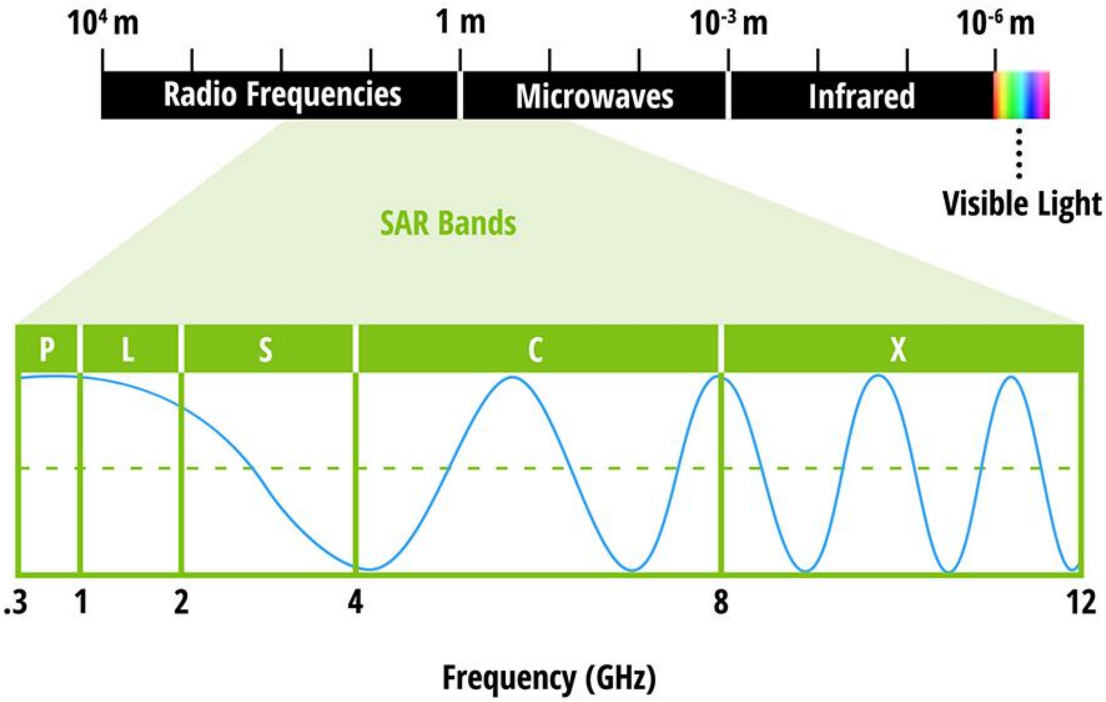

Figure 2. The electromagnetic spectrum with microwave bands shown.
Source: Herndon et al. (2020)

1.3.2 Platforms

Typical platforms for remote sensing can be spaceborne (satellites), airborne (planes, helicopters), or ground-based (i.e., drones, vehicle-mounted sensors) (Lechner et al., 2020). While some consider drones (i.e., UAVs) ground-based, many authors consider this platform airborne. Typical sensors for spaceborne platforms include optical sensors (multispectral and hyperspectral) and SAR. Multiple similar satellites can be used to obtain frequent (i.e., almost daily) observations of the Earth (this grouping of satellites is referred to as a constellation) (Inoue, 2020). While most sensors, especially satellites, are not multispectral or hyperspectral (Inoue, 2020), there are sensors with such capabilities available and they are discussed further in Section 3.0. Individual satellites may be outfitted with multiple sensor types. Optical sensors, SAR, and LiDAR are commonly used with airborne platforms. Drone-based sensors may include multispectral sensors and LiDAR. Ground-based sensor platforms, such as those for fixed sensor networks or mobile sensors, typically use passive sensors (Section 1.3.1).

Recent technological advancements have made all sensors available on all platforms, including less common combinations such as SAR on UAVs. Each platform has pros and cons related to its application, although UAVs are being increasingly used due to their ability to capture very high spatial resolution data (Lechner et al., 2020). Considerations that may impact which platform is appropriate for different applications include size of the site (will impact the required spatial resolution), parameters being measured (spectral resolution), and the frequency of measurements (temporal resolution). Some common sensors and platforms, and their spatial resolution, are outlined in Table 1.

Table 1. Common remote sensing sensors and platforms, with their respective spatial resolution. Table adapted from C-CORE (2019).

Platform	Sensor	Spatial Resolution
Airborne	Panchromatic	<50 cm
	Multispectral	<50 cm
	Hyperspectral	2 to 5 m
Spaceborne	Panchromatic	<1m
	Multispectral	1 to 10 m
	Synthetic aperture radar (SAR)	1 to 10 m

A survey conducted by Powter et al. (2016) in Alberta indicated that satellite imagery is the most commonly used method of environmental data collection at a regional to provincial scale, followed by in-field manual collection. However, it should be noted that recent advances have allowed for the application of very high spatial, spectral, and temporal resolution data on smaller-scale projects (J. Kariyeva, personal communication, April 21, 2021). Other methods of EO/RS data collection are listed from more to less frequently used: plane, drone/UAV, fixed sensor networks, mobile sensors, and helicopter. While EO/RS is not expected to completely replace manual field measurements in reclamation assessments, over time EO/RS technologies are expected to result in reduced field data collection. Survey respondents used multispectral imagery most frequently, while hyperspectral imagery and radar were often considered not applicable; however, it is not clear if hyperspectral imagery and radar have limited use due to cost, lack of familiarity, or previous poor experience. Additionally, in the last few years, SAR applications have increased dramatically (J. Kariyeva, personal communication, April 21, 2021), indicating that the use of these technologies is changing. Survey respondents indicated that spatial resolution <2.5 m was most appropriate for their needs, followed by resolution from 2.5 to 10 m.

2.0 METHODS

A review of the literature on EO/RS and digital technologies was completed using scientific papers, scientific reports, and workshop reports.

Keywords for the literature search included:

- Remote sensing
- Earth observation
- Digital technology
- Sensors
- Radar
- SAR
- InSAR
- LiDAR
- Multispectral
- Hyperspectral
- Proximal soil sensors
- Reclamation
- Landscape
- Topography
- Elevation
- Slope
- Surface features
- Soil properties
- Species composition
- Invasive species
- Understory
- Overstory

Given the breadth of available literature and advances in technology, we focused on more recent studies (2010 to present). However, some studies prior to 2010 were included where they provided insight not available from more recent studies and to describe changes in the available technology over time. The literature review was focused on the use of remote sensing to assess parameters that are relevant to the reclamation certification criteria in Alberta (as outlined in Section 1.0).

The information obtained from the literature is evaluated in Section 3.0. Section 3.0 is organized to first provide an overview of relevant EO/RS studies focused on monitoring reclamation and revegetation. Further detail is then provided on vegetation parameters (i.e., species composition including identification of invasive species, understory vegetation, and overstory vegetation). This is followed by an assessment of the use of EO/RS technologies for evaluating landscape features and soil. The evaluation of water bodies and wetlands are also considered. Finally, an assessment specific to agriculture is conducted, given that cultivated systems are very different from forested systems, with differing reclamation criteria.

3.0 RESULTS AND DISCUSSION

3.1 Revegetation and Change Detection

3.1.1 Review of EO/RS and Digital Technology Applications

The use of remote sensing techniques to assess revegetation success and monitor changes in vegetation over time is common in the scientific literature. Typically, multispectral imagery has been used to develop vegetation indices to assess changes in vegetation cover and class over time; however, the development of high spatial resolution technologies and ability to combine sensors with different platforms has expanded the ability to assess vegetation via remote sensing in recent years. Vegetation indices, and their application to different revegetation and reclamation scenarios, are discussed in this section.

Normalized difference vegetation index (NDVI) appears to be one of the most used metrics to monitor vegetation changes over time. NDVI is defined as the ratio between the difference of near infrared (NIR) and red (RED) over the sum of NIR and RED reflectance in percent, i.e. NDVI = (NIR-RED)/(NIR+RED). The NDVI index ranges from -1 to 1 with -1 representing oceans, 0 representing landscapes with no green leaves, and 1 representing landscapes with healthy green vegetation. NDVI typically utilizes multispectral data from satellite imagery (Karan et al., 2016). Other indices for assessing vegetation include: (simple) ratio vegetation index (SRVI or RVI), enhanced vegetation index (EVI), and soil adjusted vegetation index (SAVI) (Chasmer et al., 2018; Karan et al., 2016). The normalized difference moisture index (NDMI) can also be used in the classification of landscape and vegetation parameters.

Karan et al. (2016) monitored changes in vegetation cover at a reclaimed coal field in India, to assess reclamation success and determine the most suitable remote sensing technique for continued monitoring. The coal field lies within a river valley, and has a humid subtropical climate to a tropical wet and dry climate. Karan et al. (2016) found that NDVI coupled with NDMI provided the best method for monitoring vegetation; EVI also showed a strong linear relationship with NDMI. Karan et al. (2016) used Landsat satellite images from 2000 and 2015, combined with GIS, to assess the relationship between vegetation health and moisture. A field validation was performed to assess the accuracy of the remote sensed data. The authors successfully delineated seven different land use and vegetation classes (vegetation classes included Dense Vegetation, Mid Dense Vegetation, Sparse Vegetation) (Karan et al., 2016).

Other authors have successfully used time-series remote sensing data to determine NDVI and assess revegetation success. Chasmer et al. (2018) used vegetation indices produced using SPOT imagery to assess vegetation changes over time and to compare with field-collected data on vegetation structure and eddy covariance flux (an atmospheric measurement technique). The study sites were within the Alberta Oil Sands Region and included 15 sites that ranged from dry to wet. Field data collection included stem density and woody biomass indicators such as diameter at breast height (DBH), basal area, and relative spacing index; foliage-based indicators included leaf area index (LAI) and stem density. Chasmer et al. (2018) found that the simple ratio vegetation index (SRVI) was a good indicator of stem density; NDVI and SAVI performed best when compared to foliage-based indicators, net ecosystem production (NEP) and gross ecosystem production (GEP), which are structural driving mechanisms for eddy covariance fluxes. Stem density and woody biomass measurements compared better with lower resolution (interpolated) pixels, while pixel to plot comparisons for LAI and canopy cover were better than using interpolated pixels. In general, higher spatial resolution (i.e., 10 m) improved the relationship between vegetation indices and structural measurements. When LAI was greater than 3 m^2/m^2 (more dense vegetation), NDVI showed decreased sensitivity, indicating limitations with using NDVI on mature sites. For sites with dense vegetation cover, the authors suggested that LiDAR may help overcome the limitations of NDVI (Chasmer et al., 2018); NDVI may not be the most appropriate technique if the goal is to compare reclaimed and undisturbed sites, or as reclamation sites mature an vegetation reaches alter seral stages.

Aerial multispectral surveys were used at the Highland Valley Copper Mine in British Columbia to assess changes in vegetation cover from 2001 to 2010 and develop high resolution maps (~3m spatial resolution) (de Saavedra Alvarez et al., 2011). The authors found correlations between vegetation cover and precipitation, relating to water retention across the site (influenced by factors such as slope and soil composition); the maps produced based on these relationships constituted valuable tools for management of site reclamation. To acquire multispectral images, the authors used a Compact Airborne Spectrographic Imager (CASI) configured to acquire images in 9 spectral bands at 2.5 m spatial resolution. NDVI was used to classify site vegetation and determine biomass. Using an algorithm, NDVI maps were classified into eleven different reclamation status classes, including classes such as stable, rapid growth, rapid decrease, affected by desiccation, disturbed not recovered; site visit and photograph data were used to inform accurate classifications (de Saavedra Alvarez et al., 2011).

Also in British Columbia, remote sensing has been used to assess the status and success of, as well as monitor, reclaimed areas of a coal mine. Straker et al. (2004) used panchromatic and multispectral data obtained with the QuickBird satellite to identify ten vegetation classes on site. The authors intended to use the information to assess post-closure objectives on older reclaimed sites and predict the trajectory of more recent reclamation initiatives. Straker et al. (2009) used satellite-based multispectral data to classify reclamation areas of the mine based on biomass cover; the intention is to utilize this information to monitor reclamation progression over a large area.

While NDVI is commonly used to assess revegetation of reclaimed or disturbed sites over time, normalized burn ratio (NBR) has been used in Alberta to assess spectral regeneration over time. NBR is calculated similarly to NDVI, but the formula incorporates both near infrared and shortwave infrared wavelengths, i.e. NBR = (NIR-SWIR)/(NIR+SWIR). Similar to NDVI, NBR is bounded between -1 and 1 with negative values representing burnt areas and positive values representing healthy vegetation. For example, in Alberta, Hird & McDermid (2020b) used a dataset comprised of 66,180 forest harvest polygons across the regions of Alberta where forest harvest occurs; the polygons ranged in size from 2 ha to over 1000 ha and encompassed harvest dates ranging from 1989 to 2012. Landsat 5, 7, and 8 satellite images were used to derive NBR, which include multispectral, panchromatic, and thermal sensors. The author concluded that the derived spectral regeneration dataset was a valuable product for providing information on vegetation recovery after harvest. In a follow-up report, Hird & McDermid (2020a) expanded on the spectral regeneration work for forest harvest disturbance, exploring challenges and opportunities to apply the workflow to other human disturbances, namely surface mining and well sites. The author concluded that there are opportunities to apply Landsat-derived NBR spectral regeneration to landscape features associated with surface mining and well sites (including sites undergoing reclamation).

Also in Alberta, multiple technologies have been used to assess reclamation sites both on forested and cultivated lands as part of the Monitoring Procedures for Wellsite, In-Situ Oil Sands and Coal Mine Reclamation in Alberta (MOPRA) project (Rochdi et al., 2014). The goal of MOPRA was to develop a geomatics-based monitoring system to support the monitoring of reclamation success in Alberta using remote sensing. Spaceborne multispectral and hyperspectral, as well as airborne hyperspectral and LiDAR data were assessed for their potential in vegetation monitoring. Sensors with a spatial resolution of 30 m or less were selected given that the wellsites being monitored ranged in size from 1 to 3 ha. Land cover and change detection maps were successfully developed as part of the MOPRA project using Landsat (multispectral) data. Tree species maps were developed with multispectral, hyperspectral, and LiDAR data. Classification accuracy varied by species – 63%, 73%, and 79% for trembling aspen (*Populus tremuloides* Michx.), black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenburg), and white spruce (*Picea glauca* (Moench) Voss), respectively, when combining multispectral and LiDAR data. Accuracies greater than 77% were reported for all species with the use of hyperspectral data. LiDAR data was used to assess canopy height and canopy fractional cover. The authors indicated that the results can be applicable to a variety of disturbances (other than well sites and coal mines, which were the focus of the MOPRA report), but further testing of the MOPRA tool is needed to integrate remote sensing with operational monitoring (Rochdi et al., 2014).

Typically, vegetation-related studies have used optical sensors (including multispectral) to develop indices for assessing vegetation parameters or have determined land use/type classes. These analyses can be particularly useful to monitor changes to an area over time (i.e., Chasmer et al., 2018; de Saavedra Alvarez et al., 2011; Karan et al., 2016), and to inform best management practices and reclamation trajectory. More specific information regarding vegetation obtained with EO/RS data is explored in sections 3.2. to 3.4.

3.1.2 Considerations for Alberta Reclamation Certification Criteria

Important considerations regarding the application of remote sensing for vegetation monitoring in reclaimed sites include:

- When utilizing satellite images to assess changes in vegetation cover and moisture over time, it is important to use near anniversary dated (images captured at approximately the same date each year) images (Karan et al., 2016; Padmanaban et al., 2017) to reduce the effects that seasonal temperature and precipitation can have on the images.
- NDVI functions on the concept that chlorophyll absorbs light in the red (665 nm) region of the electromagnetic spectrum, while the mesophyll leaf structure of plants reflects light in the near infrared (776 nm). Therefore, NDVI is proportional to healthy green vegetation, but can underestimate biomass if plants have lost chlorophyll due to factors such as desiccation (de Saavedra Alvarez et al., 2011).
    - For example, de Saavedra Alvarez et al. (2011) found that grass-dominated systems tended to have wide variations in greenness depending on precipitation, but this variation in greenness was only associated with moderate biomass changes.
    - At the site-scale, practitioners should be aware of this effect when using remotely sensed data for decision making as it could be a confounding factor or used as an indicator.

  - Other indices, such as NBR, are being explored for their use in assessing spectral regeneration at surface mining and well sites in Alberta and may help overcome some of the challenges associated with NDVI.
- NDVI derived from remote sensing data may not be appropriate for sites with dense vegetation; active sensors such as LiDAR may be more appropriate in such circumstances (Chasmer et al., 2018).
- Remote sensing data is typically calibrated with in-field measurements to estimate biomass from NDVI (de Saavedra Alvarez et al., 2011). It may be possible to calibrate and validate remotely sensed data with offsite data, assuming the vegetation species and geology are the same. Spectral libraries could help to reduce the need for in-field calibration and validation. Spectral libraries exist for geological materials (i.e., Arizona State University spectral library, USGS spectral library), but application of the Arizona library in Canada has not been successful due to differences in spectral imagery (De Abreu et al., 2015). The USGS has a spectral library which includes plants and vegetation communities (USGS, n.d.), but the relevance to Alberta species would need to be confirmed.
- Rochdi et al. (2014) evaluated hyperspectral and LiDAR data in addition to multispectral data:
  - LiDAR is costly, which can prohibit a time-series approach.
  - LiDAR is typically used for developing terrain models, and not monitoring vegetation canopy.
  - Both these technologies appeared promising for reclamation monitoring in Alberta. Hyperspectral and LiDAR data are explored further in Sections 3.2 to 3.4.

The techniques described above largely used multispectral data to evaluate revegetation of reclaimed systems. However, there are limitations to multispectral data. Because of the relatively low spectral resolution, information on the structure of ecosystems is limited (Lyu et al., 2020). Additionally, time and space scales can complicate the interpretation of multispectral data (Lyu et al., 2020). Hyperspectral remote sensing can fill in some of the gaps associated with multispectral data. Hyperspectral data provides high resolution and a large amount of data, and has been used to identify vegetation types, species composition, and growth status (Lyu et al., 2020). There are limitations associated with hyperspectral data, including limited coverage areas and application; thus, hyperspectral data is often used in combination with multispectral data. Hyperspectral techniques are explored further in section 3.2. Additionally, active sensors such as LiDAR and SAR can be effective at assessing vegetation structure and are discussed further in section 3.3 and 3.4.

3.2 Species Composition

3.2.1 Review of EO/RS and Digital Technology Applications

Researchers have used hyperspectral remote sensing to determine vegetation species composition. At the foliar level, different plant species should have a unique molecular composition which can be detected with hyperspectral sensors. The major groups of photosynthetic organisms (terrestrial plants, aquatic plants, mosses, lichens, algae, and bacteria) have distinct spectral signatures that could be used with hyperspectral remote sensing to differentiate vegetation, potentially to species level (He et al., 2011).

Available hyperspectral sensors include Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), Airborne Imaging Spectroradiometer for Applications (AISA), Compact Airborne Spectrographic Imager (CASI), Hyperion, and HyMap (He et al., 2011); these sensors have been used to identify vegetation at the species level in a variety of ecosystems, from grasslands to riparian areas to forests. For example, Clark et al. (2005) used hyperspectral imagery (1.6 m resolution) to differentiate tree species in an old growth tropical forest in Costa Rica using leaf-, pixel-, and crown-scale spectra. Overall, high accuracy was achieved, although different classifiers achieved varying accuracy. Leaf-scale classification had 100% accuracy, and pixel-scale spectra were classified with 88% accuracy (Clark et al., 2005).

Hyperspectral sensors, used to differentiate vegetation species, can be particularly useful in the identification and monitoring of invasive species. Hyperspectral sensors have been applied in cultivated lands, grasslands, shrublands, wetlands, and riparian areas to identify a variety of invasive species including Canada thistle (*Cirsium arvense* (L.) Scop.), which is a common invasive in Alberta (i.e., Andrew & Ustin, 2010; Hestir et al., 2008; Lawrence et al., 2006; Miao et al., 2006; Narumalani et al., 2009; Pengra et al., 2007; Pu et al., 2008).

In a study of a grassland community within Inner Mongolia, China, researchers assessed the use of hyperspectral remote sensing to assess grassland degradation (Lyu et al., 2020). Typical grassland species in the area include *Stipa grandis*, *Leymus chinensis*, *Cleistogenes squarrosa*, *Allium ramosum*, and *Artemisia scoparia*. In-field measurements included spectral curves for the five typical species collected using an ASD Hand Held 2 Spectrometer, plant height, density, crown width, coverage, and biomass for each species. The spectral and hyperspectral data was used to determine vegetation classes (lightly degraded, moderately degraded, and severe degraded grassland) and identify the five typical species; certain species were identified as indicators of grassland degradation (Lyu et al., 2020). The classification accuracy of the grassland classes varied from 17% to 85%, and classification accuracy of the different species varied from 41% to 82%. By employing the root mean square error (RMSE), a commonly used metric for assessing spectral un-mixing accuracy, the authors achieved an accuracy of up to 95% in classifying endmembers. According to their findings, this level of accuracy suggests an ideal classification and identification performance. (Lyu et al., 2020). While hyperspectral analysis appears suitable at the reclamation site scale, the authors noted that hyperspectral analysis is not suitable for regional scale analysis (Lyu et al., 2020).

3.2.2 Considerations for Alberta Reclamation Certification Criteria

Important considerations regarding the application of remote sensing for assessing species composition include:

- Hyperspectral remote sensing, to monitor individual species or gather data on species composition, is more suited to open environments (i.e., grasslands, agriculture, young reclamation sites). Hyperspectral sensors could also be useful to monitor invasive species in agricultural fields or young reclamation sites in Alberta.
    - In Alberta, most of the relevant invasive species are herbaceous or shrubby. If a vegetation canopy was established on a reclamation site, hyperspectral data would not be recommended for monitoring invasive species or understory species; however, collecting remotely sensed data during leaf-off conditions or with the use of drone- or ground-based platforms could improve measurements.
- While hyperspectral remote sensing is well suited for species level classification, it is very costly to acquire data for larger areas and for multiple timepoints.
- Combining hyperspectral and multispectral data can provide more information and assist in achieving adequate spectral resolution.

3.3 Understory Vegetation

3.3.1 Review of EO/RS and Digital Technology Applications

The ability to assess understory vegetation is important when monitoring reclamation sites, as many reclamation sites in Alberta are on the trajectory towards forested ecosystems. However, as noted in Section 1.3, passive sensors (optical and thermal) cannot penetrate through overstory vegetation. The limitations of passive sensors to assess understory vegetation can be addressed in two ways: (1) using active sensors to study understory, or (2) using UAVs or ground-based platforms to study the understory.

Active sensors, such as SAR and LiDAR, can penetrate through a vegetation overstory (Mitchell et al., 2017). These technologies can be particularly useful in situations like Chasmer et al. (2018) described, where the overstory is too dense to observe understory vegetation or landscape parameters. The sensors have different abilities to penetrate the canopy, as described in Section 1.3.1. Additionally, it should be noted that when utilizing LiDAR, the number of pulses returned from the overstory and understory can differ and it may be difficult to determine whether pulses are returned from the ground surface or vegetation; Hamraz et al. (2017) found 90% of pulses reached the overstory and only 60% reached the understory when utilizing airborne LiDAR. Interferometric SAR (InSAR), polarimetric SAR (PolSAR), and polarimetric interferometry SAR (PolInSAR) can be particularly useful in these cases, providing radar returns from the ground surface and vegetation canopy which can be differentiated (European Space Agency, 2003; Mitchell et al., 2017; Shimoni et al., 2009). SAR and LiDAR have been used to assess gaps in forest canopies and identify roads/trails beneath the canopy (Mitchell et al., 2017). SAR and LiDAR are also highly sensitive for measuring forest volume and biomass (Mitchell et al., 2017).

SAR combined with optical imagery can improve the differentiation between forest growth stages with over 75% accuracy, as demonstrated in Australia (Lucas et al., 2014). LiDAR has been used to assess the vertical distribution of woody vegetation, including height (Mitchell et al., 2017). In an example from Costa Rica, LiDAR-measured tree height was compared to field-collected data, and a root mean square error of 1.34 m was achieved (Castillo et al., 2012). The examples discussed in this paragraph relate to satellite-based applications of SAR and LiDAR, but these technologies can also be used with UAVs.

In addition to using active sensors, drone- and ground-based platforms can allow for assessment of the understory. Numerous studies investigating the use of UAVs for monitoring the understory have been published in last 10 years, and Hernandez-Santin et al. (2019) reviewed 18 such studies to determine the capability of UAVs to monitor and identify understory vegetation. Passive and active sensors were used to identify and count species, identify and monitor invasive species, and determine biomass estimates in the papers reviewed by Hernandez-Santin et al. (2019). Passive sensors were used most commonly (including RGB, multispectral, and hyperspectral), and active sensors were used in three of the studies. The areas assessed varied in size from 0.00007 ha to 1,520 ha (latter obtained with multiple plots), with spatial resolution, reported in only seven of the papers, of 3 to 200 mm per pixel (3 mm resolution obtained when extent covered was 0.00007 ha). The reported success in monitoring understory communities varied between the studies given the assessment goals and technologies used. The authors concluded that while there are challenges associated with monitoring understory vegetation using passive and active sensors on UAVs, UAVs can be flown close to vegetation or through the foliage/under a forest canopy (although not currently routine), to obtain high spatial resolution. With the use of UAVs to collect data, there may be time and cost challenges associated with the collection of multi-temporal data.

Two of the studies reviewed by Hernandez-Santin et al. (2019) were conducted in Canada, and are described in the following two paragraphs. In Leduc & Knudby (2018), RGB sensors mounted to UAVs were used with 76% accuracy to identify wild leek in Gatineau Park, Quebec. The authors noted that temporal variation in plant phenology can be used to improve accuracy, as understory species may have similar spectral signatures; planning flight times to coincide with phenological changes can make the differences in spectral signatures stronger between species, thus improving accuracy (Leduc & Knudby, 2018). Other authors have indicated that temporal changes in phenology play a role in successful vegetation classification (Müllerová et al., 2017; Van Auken & Taylor, 2017).

In a study at the Petawawa Research Forest in Ontario, Vepakomma & Cormier (2017) used LiDAR with a helicopter platform to assess tree heights and understory vegetation. As noted by Hamraz et al. (2017), returns (or pulses) from the ground surface were low (approximately 2%), and varied by year due to seasonality (measurements in the fall had greater returns as the vegetation was less dense due to leaf loss) (Vepakomma & Cormier, 2017). Tree height was successfully measured, and correlated strongly with field-collected data (Vepakomma & Cormier, 2017). The authors state that growth assessment and identification of mortality at the individual tree level is realistic with the LiDAR system evaluated (Vepakomma & Cormier, 2017). Additionally, the authors were able to determine from which vegetation structural class the LiDAR returns originated: high vegetation, medium vegetation, low vegetation, and ground.

In South Africa, Mafanya et al. (2017) used RGB sensors with UAVs to identify invasive species based on phenology, but noted this was not possible where an overstory was present. Utilizing UAV-borne LiDAR in Austria, Mandlburger et al. (2016) collected data with similar point cloud densities (number of coordinates per unit area) both when leaves were on and off (overstory present or not present), indicating that LiDAR could be used effectively to monitor the understory even with an overstory present.

In the Acadian forest of New Brunswick, satellite imagery and LiDAR were combined to assess sapling density in regenerating forest stands (Landry et al., 2020). Compared to LiDAR alone, combining the technologies did not improve sapling density measurement accuracy or reduce the negative influence of canopy cover on measurements; compared to satellite imagery alone, combining the technologies improved accuracy by approximately 15% (Landry et al., 2020).

In Australia, 3D remote sensing has been used to assess understory vegetation (utilizing 3D point clouds generated with a Trimble TX8 scanner or mirrorless cameras), and a method developed for validating these measurements utilizing a field frame (Hillman et al., 2019). The authors found a high correlation between remote sensing and field-collected data where the understory vegetation had a large mass or surface area (i.e., leaves, twigs, and bark $\geq$0.02 m in diameter). However, in complex environments with low mass/surface area understory vegetation, correlations were not as high (Hillman et al., 2019). The findings from Hillman et al. (2019), in terms of complex environments yielding lower accuracy, mirror the findings of Chasmer et al., 2020) (Section 3.7).

3.3.2 Considerations to Alberta Reclamation Criteria

Important considerations regarding the application of remote sensing for assessing understory vegetation include:

- Optical sensors (i.e., RGB, multispectral, hyperspectral) are more appropriate for assessing vegetation in open areas or where a dense overstory is not present, or where platforms such as UAVs can be used.

- When using optical sensors, planning flight times to coincide with phenological changes in vegetation can make the differences in spectral signatures stronger between species, thus improving accuracy (Leduc & Knudby, 2018).
- Active sensors (i.e., SAR, LiDAR) are more suited to monitoring understory vegetation as they can penetrate through overstory vegetation.
- Most radar returns (i.e., when using LiDAR) may not penetrate the overstory. Polarimetric and interferometric SAR (InSAR) can be useful in these cases.
- Despite challenges associated with assessing understory vegetation, especially in complex environments (i.e., forests), active sensors have effectively been deployed to monitor understory vegetation. For Alberta's forested reclamation sites, active sensors provide the best remote sensing technologies for assessing vegetation height by structural layer. For example, results from Vepakomma & Cormier (2017) suggest that LiDAR could be used to assess vegetation structure for Alberta reclamation certification.
    - At this time, LiDAR is considered a cost prohibitive technology (Rochdi et al., 2014), typically used for assessing landscape features and terrain, but the literature indicates it is a promising technique for assessing vegetation structure.
- Using drone-based platforms or high-cost sensors (i.e., LiDAR) may reduce the ability to collect data from the same location multiple times; this potential limitation should be taken into account when considering project goals (i.e., is the goal to monitor vegetation over time or collect data from a single point in time?).

3.4 Overstory Vegetation

3.4.1 Review of EO/RS and Digital Technology Applications

Passive and active sensors may be used to assess overstory parameters such as aboveground biomass, tree species, height, canopy structure, and crown diameter among others. For example, tree species have been identified using hyperspectral sensors (Asner et al., 2006; Clark et al., 2005). Drone-based RGB sensors have been used to measure canopy density (Van Auken & Taylor, 2017). LiDAR and SAR have both been successfully used to measure tree height and the vertical distribution of woody vegetation (Castillo et al., 2012; Mitchell et al., 2017). Parameters such as canopy depth, crown structure (i.e., crown diameter), and tree height have been determined using airborne LiDAR (Vepakomma & Cormier, 2017). In the Acadian forest of New Brunswick, satellite imagery and LiDAR were combined to assess sapling density in regenerating forest stands (Landry et al., 2020).

High spatial resolution can be obtained with current sensor technologies. In Costa Rica, LiDAR was used to categorize trees by height into bins, with each bin representing an increase in height of approximately 0.31 m (Castillo et al., 2012); while this is a very different ecosystem than the forests of Canada, this study provides evidence that good estimates of tree height can be obtained with LiDAR. However, LiDAR is an expensive technology, which limits its use for reclamation monitoring especially in time-series analysis.

Photogrammetry offers a less expensive source of 3D remote sensing data, compared to LiDAR. Photogrammetric point clouds (PPCs), generated from consumer-grade digital cameras affixed to UAVs, have been used to assess forest structure and phenology (Hird et al., 2017b). PPCs are well-suited to assessing overstory vegetation, but not understory vegetation as they cannot see below a dense forest canopy. In Alberta, Hird (2017b) compared PPC-based vegetation metrics (obtained via digital camera mounted to a UAV) to in-field data collection. The study area covered approximately 5,000 km^2 of boreal forest and foothills regions of Alberta and included nine study sites each representing a reclaimed well site. Compared to in-field measurements, PPC metrics were successful in predicting vegetation structural parameters such as average and maximum vegetation height. PPC metrics were less useful for estimating ground-measured vegetation cover. The authors noted that challenges associated with vegetation cover measurements could be related to different measurement approaches between PPC and field data collection, and subjective judgement when collecting in-field data. Overall, the authors concluded that UAV-based PPC data could complement, and potentially supplement, traditional in-field measurements of vegetation structure (Hird et al., 2017b).

More recently developed techniques, such as InSAR and PolInSAR, have been used to accurately assess canopy height. Within the Beaverhills Biosphere near Edmonton, LiDAR was used to validate PollInSAR models of canopy height from a boreal forest ecosystem based on TanDEM-X spaceborne SAR data (Schlund et al., 2019). Canopy height was estimated with moderate accuracy (5 to 14 m) with the TanDEM-X data, depending on the model used (Schlund et al., 2019), which may not be sufficient for small-scale reclamation sites.

There are limitations to the various remote sensing technologies discussed, and results can vary across different ecosystems. For example, in a study of a low-biomass transition from non-forest to conifer-dominated boreal forest stands, the accuracy of biomass estimates using airborne and spaceborne LiDAR and SAR were improved when aboveground biomass was higher (gradient from 0 to 60 Mg ha^{-1}) (Montesano et al., 2014). The authors noted that at the site level, there are difficulties in achieving accurate aboveground biomass estimates with spaceborne sensors, especially with biomass below 80 Mg ha^{-1} (Montesano et al., 2014).

3.4.2 Considerations for Alberta Reclamation Criteria

Important considerations regarding the application of remote sensing for assessing overstory vegetation include:

- Data collection with passive sensors can be disrupted by cloud cover and haze; therefore, in some cases active sensors (i.e., SAR, LiDAR) may be more appropriate. Utilizing UAVs can also overcome the challenges associated with cloud cover.
- Photogrammetry is well-suited for assessment of overstory vegetation structure, offering a lower-cost option for generating 3D point cloud data compared to LiDAR.
- If understory vegetation is also of interest, the presence of overstory vegetation creates challenges. In these cases, active sensors or drone-based platforms can be used to overcome these challenges.
- Spaceborne sensors may not provide adequate spectral resolution for small-sized reclamation sites in Alberta.
- SAR is currently used on an operational scale in Alberta, however technologies such as InSAR and PolInSAR are newer and may not be operationally feasible at this time.

3.5 Landscape Features

3.5.1 Review of EO/RS and Digital Technology Applications

Remote sensing technologies such as LiDAR and SAR are well suited to assessing parameters such as elevation (developing digital elevation models [DEMs], digital surface models [DSMs], digital terrain models [DTMs]) and slope. InSAR may be particularly useful for measuring changes in topography accurately, as the measurements can be at the centimetre scale (Herndon et al., 2020). Satellites that carry panchromatic and multispectral sensors capable of capturing stereoscopic images—such as WorldView-1, WorldView-2, and WorldView-3—can also be used to generate DEMs (University of Minnesota, 2017). Topography, elevation, and slope estimates obtained from remote sensing data are generally more accurate in simple systems or those with shorter vegetation (i.e., bare ground or agricultural land compared to complex forests) (Zhu et al., 2020). Spaceborne, airborne, and drone-based remote sensing systems can be used to assess topography.

Airborne LiDAR has been used to study the impact of land cover and slope on remote sensing derived elevation data. For example, Hodgson et al. (2005) investigated the effect of land cover classes such as grassland, scrub/shrub, pine forest, deciduous forest, and mixed forest in North Carolina, USA (45.65 km^2). Remote sensing data was collected during leaf off conditions. Land cover classes with taller vegetation tended to have larger errors in the estimated elevation (Hodgson et al., 2005). Slope in the study area ranged from 0 to 10°, and greater slope did not tend to result in higher elevation error. However, remote sensing derived models tended to underpredict the true slope when slope was greater than 2°. Additionally, the LiDAR-derived elevation tended to underpredict true elevation (Hodgson et al., 2005).

Digital elevation models (DEMs) are particularly useful for assessing topographic features. DEMs provide a digital representation of terrain, where each pixel represents a height above a datum. Currently, DEMs are most often created via remote sensing techniques (i.e., photogrammetry, airborne and spaceborne InSAR, and LiDAR) (Hawker et al., 2018). There are numerous global, open-access DEMs available, which are largely created with spaceborne InSAR (Hawker et al., 2018; Zhu et al., 2020), however DEMs can be developed at a smaller scale using drone-based photogrammetry (Coveney & Roberts, 2017).

Estimates of vegetation parameters with LiDAR are often based on relative height above a DEM. There has been much work evaluating different data processing methods for improving the accuracy of LiDAR-derived DEMs (Bater & Coops, 2009). Accurate DEMs are especially important in mountainous regions, where there are large differences in elevation (Proy et al., 1989). The accuracy of global DEMs is often limited in forested systems.

Recently, Zhu et al. (2020) investigated the use of ICESat-2 data to evaluate terrain slope data under forested land in the United States. ICESat-2 carries the Advanced Topographic Laser Altimeter System (ATLAS) sensor. The estimated slopes using ICESat-2 data were validated with airborne LiDAR and compared to two global DEMs. ICESat-2 data were found to be appropriate for estimating slope in complex forested systems, as the estimates correlated well LiDAR data and performed better than the global DEMs evaluated (Zhu et al., 2020).

3.5.2 Considerations for Alberta Reclamation Criteria

Important considerations regarding the application of remote sensing for assessing landscape features include:

- LiDAR, SAR, and InSAR are well suited for assessing topography, elevation, slope, and for developing DEMs.
- There are numerous global DEMs that have been developed. DEMs can be developed on a smaller scale via drone-based photogrammetry, which may be more suitable for small reclamation sites.
- LiDAR is generally considered an expensive technology (Rochdi et al., 2014).
- On forested reclamation sites, LiDAR derived elevation and slope data is likely to be less accurate than on grassland sites or cultivated land.

- Assessments of topography and elevation can be improved during leaf-off conditions (i.e., fall or winter).
- Recent technological advances (i.e., ICESat-2) appear promising for assessing slope in forested systems, but likely require further validation before use on an operational scale.

3.6 Soil

3.6.1 Review of EO/RS and Digital Technology Applications

Researchers have used remote sensing techniques to assess soil chemical and physical properties and soil stability. Optical and microwave (radar) sensors have been typically used to assess soil properties via remote sensing at regional and more coarse scales (Mulder et al., 2011). Soil texture, mineralogy, iron, organic carbon, carbonate content, salinity, and moisture have all been assessed with remote sensing techniques and proximal soil sensors (discussed further in Section 3.6.1.2) (Mulder et al., 2011).

For example, in a study from a semiarid region of Arizona, with typically desert vegetation, Landsat Thematic Mapper (multispectral sensor) derived NDVI was used to predict surface soil texture and coarse fragments, and modeled with SVM classification (Maynard & Levi, 2016). The author used numerous multispectral images (530) over a 28 year time series (termed "hyper-temporal" remote sensing), and found this method to have higher classification accuracy than mono-, bi-, or multi-temporal remote sensing (Maynard & Levi, 2016). It should be noted that the study area was 6,065 ha, and the spatial and spectral resolution of sensors, as well as the timeframe, would have to be considered if this method were applied on small reclamation sites.

Soil colour has been assessed with hyperspectral proximal soil sensing and multispectral remote sensing, however the application of such technologies was for very large areas (Poppiel et al., 2019). Other authors have transformed Munsell colour data to red, green, and blue colour coordinates for application to satellite-based RGB sensors (Escadafal, 1993).

In an example from an agricultural system, soil salinity was mapped at a regional scale in Pakistan using spaceborne multispectral data (Abbas et al., 2013). The authors successfully delineated different land use classes based on soil salinity, and found a relationship between salinity and the water table (Abbas et al., 2013). While this case study highlights the capabilities of remote sensing in assessing soil properties, it is not highly relevant to the scale at which reclamation assessments take place in Alberta. Ground-based techniques, such as proximal soil sensors (Section 3.6.1.2) would be more suitable for site-based assessments.

In areas with sparse vegetation, success in measuring soil properties with optical and microwave sensors has been reported with spaceborne, airborne, and ground-based platforms (Mulder et al., 2011). In areas with dense vegetation, assessment of soil properties typically relies on indirect indicators, such as vegetation groups and productivity (Mulder et al., 2011). In Alberta, the use of remote sensing to assess soil properties may be limited, especially in forested ecosystems. However, there are ground-based sensors available that could reduce sampling and analysis costs (Sections 3.6.1.1 and 3.6.1.2).

3.6.1.1 Chemical and Physical Properties – Reflectance Spectroscopy

Digital technologies have been investigated for their potential to reduce costs associated with the collection and analysis of soil data. Acquisition of data on soil properties (i.e., moisture, soil organic carbon

[SOC], total nitrogen [TN], salinity, and pH) can require extensive sampling efforts, especially when the goal is to map soil properties for an area or region. Reflectance spectroscopy can be used to predict soil properties, providing a means of reducing the costs associated with extensive sampling and laboratory analysis. Reflectance spectroscopy can provide rapid, non-destructive results, thus reducing sampling time. Reflectance spectroscopy has successfully been used in Manitoba, Ontario, and more recently Alberta to predict soil properties (Martin et al., 2002; Sorenson et al., 2017; Xie et al., 2011). Other authors report prediction of soil properties such as SOC, salinity, soil moisture, soil colour, and heavy metals utilizing near-infrared reflectance spectroscopy (Mohamed et al., 2018; Poppiel et al., 2020).

In Alberta, Sorenson et al. (2017) had success predicting SOC and TN using field-measured reflectance spectroscopy (in Chernozems, Luvisols, and Solonetz), but noted that improvements to the pH model were needed for pH values below 6.5. Spatial clustering of carbon and nitrogen in soil was assessed by Sorenson et al. (2018) in soils from Alberta and Saskatchewan (including Chernozems, Gleysols, and Luvisols). Carbon and nitrogen distribution in soil was assessed within topsoil and subsoil in Alberta using reflectance spectroscopy (Sorenson et al., 2020).

3.6.1.2 Chemical and Physical Properties – Proximal Soil Sensors

Proximal soil sensors (PSS) are field-based sensors which obtain signals from soil when close to or in contact with soil, and can be used to assess various soil properties (Rossel & Adamchuk, 2013). These sensors are typically vehicle-mounted, but may also be handheld (Grunwald, Vasques, & Rivero, 2015); for example, smartphone-based and other handheld sensors are considered proximal, and are used in forestry (Talbot et al., 2017). Proximal soil sensors offer advantages over traditional in-field soil collection followed by subsequent laboratory testing and remote sensing. In agricultural fields, where manual soil sampling may be limited, or in areas where grid or random sampling is used, variation in soil characteristics may be underestimated (Grunwald et al., 2015; Rossel & Adamchuk, 2013). At remote forested sites, PSS could reduce the number of samples that must be collected and carried out. Where numerous soil samples are collected, there is a high cost associated with collection and laboratory analysis. Measurements collected with PSS are available almost instantly and require significantly less manual sampling. Therefore, PSS offer a cost-effective, and less labour-intensive, means of obtaining real-time soils information under field conditions (Rossel & Adamchuk, 2013).

There are many different types of PSS available based on measurement (invasive versus non-invasive), energy (passive versus active), operation (mobile versus stationary), and inference (direct versus indirect) (Rossel & Adamchuk, 2013). Proximal soil sensors are also categorized based on the portion of the electromagnetic spectrum used, including: gamma rays; x-rays; ultraviolet, visible and infrared spectra; microwave wavelength sensors; radio wavelength sensors; magnetic, gravity and seismic sensors; electrical resistivity and induced polarization; ion-sensitive electrodes and ion-sensitive field effect transistors; and mechanical sensors (Rossel & Adamchuk, 2013). To measure a variety of soil properties, a multisensory network is likely required (Rossel & Adamchuk, 2013). Additionally, Grunwald et al. (2015) suggest combining PSS and remote sensing data.

In an agricultural field with mineral and organic soils in Quebec, PSS were used to measure soil organic matter, pH, lime buffer capacity, calcium, magnesium, and aluminum (Ji et al., 2019). In a study from Brazil, PSS were used successfully to assess soil organic carbon (SOC), clay content, bulk density, soil moisture, and cation exchange capacity in a pasture (Vasques et al., 2020). Additionally, proximal sensors can be used to assess spatial and temporal changes in vegetation (Adamchuk et al., 2018). Recently, there have been numerous papers discussing the use of both proximal sensors and remote sensing to assess soil contamination, vegetation stress, and forest management (including terrain models, microtopographic soil modelling, and tree measurements) (Gholizadeh & Kopačková, 2019; Gholizadeh et al., 2018; Talbot et al., 2017).

In Alberta, proximal soil sensors have been evaluated for use in the long-term monitoring of soil properties at reclamation sites (Degenhardt et al., 2014; Drozdowski et al., 2012; Small & Underwood, 2015). In an initial study by Drozdowski et al. (2012), two sensors (EM induction and soil penetration resistance) were used to take the following measurements in agricultural fields and were compared to traditional laboratory analysis: soil resistance (measured with digital and analog penetrometers in the field), soil moisture, soil temperature, and bulk density. The sensors had limited applicability at temperatures below 0°C. The sensor, assessment parameters, and specific area all played a critical role in evaluating reclamation success. While some sensors and parameters were appropriate in certain areas, they were not applicable to others. Soil penetration resistance appeared more promising than EM induction. The authors questioned the applicability of the two sensors in the long-term monitoring of reclamation success on agricultural land given their lack of sensitivity on sites that had been reclaimed.

In a continuation of the initial study, Degenhardt et al. (2014) evaluated three proximal soil sensors (P4000 spectrophotometer probe, OpticMapper and electronic tiller) to monitor reclamation success at agricultural and industrial sites (i.e., wellsites, mines) across Alberta. The following parameters were measured directly by the sensors: spectrum reflectance, apparently electrical conductivity, insertion force, dual wavelength reflectance, and magnitude of mechanical resistance. The following parameters were measured indirectly: total organic carbon, organic matter, nitrogen, pH, electrical conductivity, cation exchange capacity, and bulk density. The P4000 spectrophotometer probe correlated well with laboratory results and was deemed the most useful technology, of the sensors assessed, for reclamation monitoring. The P4000 spectrophotometer probe was able to effectively monitor soil properties on sites with variable soil conditions.

Based on the studies described above, Small & Underwood (2015) compared the efficacy of the spectrophotometer P4000 probe and OpticMapper to a complete conventional soil assessment on two reclaimed and cultivated wellsites in Alberta. Recommendations for the use of these technologies for long-term monitoring of reclaimed sites were developed, with an Alberta-specific focus. These instruments offer many advantages as they produce accurate results and more data points than conventional sampling, which makes deployment of these technologies a cost-efficient alternative to conventional sampling. However, the parameters measured can be limited, and therefore combining PSS with a level 1 detailed site assessment provides a powerful tool for evaluating site conditions for land use planning and management.

While PSS are not likely to completely replace soil sample collection and analysis, they provide an opportunity to reduce costs associated with sample collection and laboratory analysis. There is an opportunity to combine proximal sensors with EO/RS to gain a more complete picture of the environment being studied. However, at least for some applications (i.e., forest management), these techniques remain largely experimental and will require improvements to become operational (Talbot et al., 2017). Recommendations for the use of these sensors for the monitoring of reclaimed sites in Alberta have already been developed. Regulators and practitioners can capitalize on the work already done in Alberta and consider complimenting sample collection with these digital technologies.

3.6.1.3 Soil Moisture

Soil moisture is one of the most common soil parameters assessed via remote sensing. Soil moisture can be assessed with optical, thermal, passive microwave, and active microwave measurements, however microwave (radar) measurements are most effective (Wang & Qu, 2009). Near surface (0 to 5 cm) soil moisture can be assessed on bare and vegetated soil with low frequency bands (X, C, and L bands) (Mohanty et al., 2017). However, Babaeian et al. (2019) reported measurement depths up to 50 cm with P-band microwaves on bare soil, and depths up to 20 cm under agricultural and rangeland use. It is possible for microwaves to penetrate forested vegetation to obtain soil moisture, with depths up to 3 cm for L-band and 10 cm for P-band sensors (Babaeian et al., 2019); however, the measurement depth depends on the soil characteristics (Mitchell et al., 2017) and P-band SAR is not expected to be available operationally until 2025 (European Space Agency – Biomass mission. Launch date 2025).

C, L, and X band sensors are onboard a variety of satellites, with new sensors having been added in recent years. Such applications, especially at C and L-band frequency have demonstrated the ability to map soil moisture with a spatial resolution of 25 to 40 km (Lechner et al., 2020; Mohanty et al., 2017). For most reclamation sites, this level of spatial resolution would not be appropriate. However, new passive and active sensors with higher spatial resolution are expected to be launched within the coming decades, opening up new markets and possibilities (Mohanty et al., 2017).

Currently, ground-based and proximal soil sensors are likely the best digital tools for assessing soil moisture, but are not highly suitable to remote reclamation sites; while some proximal sensors are handheld, many are vehicle-mounted (Grunwald et al., 2015). Ground-based sensors can be used to assess soil moisture and provide data to validate satellite-based soil moisture data. For example, cosmic ray neutron probes (CRNPs) with Cosmic-ray Soil Moisture Interaction Code (COSMIC) provide the ability to assess soil moisture, and have been used to validate satellite-based measurements (Mohanty et al., 2017; Montzka et al., 2017). However, the extent (field size) over which CRNPs are used can vary from 500 to 3,000 km^2, which is much larger than a typical reclamation site. Neutron probes and time domain reflectometry (TDR) sensor arrays are more suitable for the reclamation site scale (Babaeian et al., 2019). In addition, wireless soil moisture networks can be deployed which send soil moisture data from a sensor to a datalogger (Babaeian et al., 2019). Wireless sensor networks are very adaptable depending on the hardware and software used, and are suited to numerous applications such as monitoring microclimate, soil, air, water, habitat, and remote industrial equipment (Taheriazad et al., 2014). In Alberta, wireless sensor networks were deployed at a forested (dominantly lodgepole pine [*Pinus contorta*]) coal mine reclamation site to measure soil moisture, temperature, relative humidity, and photosynthetically active radiation (Taheriazad et al., 2014). Section 3.6.1.2 provided information on proximal soil sensors which can also be used to assess soil moisture more efficiently than manual sampling.

3.6.1.4 Erosion and Subsidence

Spectral data, used to derive NDVI (as explored in Section 3.1.1), can be used to assess erosion potential. NDVI values below 0.3 are typically associated with bare soil or very sparse vegetation (Robichaud et al., 2020). NDVI values can be used to assess areas with dense vegetation and areas with bare soil. Bare soil may be indicative of areas with high erosion potential, and to assess erosion potential, NDVI should be used in combination with other metrics such as slope.

In a study by Robichaud et al. (2020) in Washington, USA, remote sensing data was compared with field-collected vegetation and erosion data in a burned forest ecosystem. Remote sensing data was acquired from the WorldView-2 satellite, collecting spectral data across visible and infrared bands. In the study, NDVI values differed where the different treatments were applied (plot sizes were 4 m wide by 25 m long) (Robichaud et al., 2020). NDVI was significantly correlated with ground cover and sediment flux; higher NDVI values were associated with higher ground cover and lower NDVI (more bare ground) was associated with higher sediment flux (Robichaud et al., 2020). The authors demonstrated a relationship between NDVI and erosion potential. Results from Robichaud et al. (2020) indicate that bare ground could be monitored on Alberta reclamation sites via remote sensing, and the information used to assess erosion potential.

In a study along the Colville River in Alaska, researchers estimated the volume of land lost due to erosion around bluffs using remote sensing (Payne et al., 2018). Orthomosaic and satellite images were gathered for different years, and included multispectral, colour-infrared, and panchromatic images. A digital elevation model was also used to estimate the volume of land lost. Because there was a sharp contrast between tundra, bluff, and water, the images could be classified with high accuracy (>95%) (Payne et al., 2018). The estimates of erosion calculated using the images and automated methods were comparable to values obtained with manual hand-digitization (Payne et al., 2018). It could be possible to utilize similar methods in other systems, provided sufficient contrast between the land and water could be obtained via the images.

Soil stability (i.e., subsidence) is typically monitored via InSAR. For example, in an agricultural area of Saskatchewan, soil subsidence rates in circular areas (approximately 1 to 2 km in diameter) were assessed with spaceborne InSAR (Samsonov et al., 2014). In Alaska, spaceborne InSAR was used to assess soil subsidence in a thermokarst landform (Liu et al., 2015). InSAR has frequently been used to assess subsidence in coastal areas (i.e., Aimaiti et al., 2018).

3.6.2 Considerations for Alberta Reclamation Criteria

Important considerations regarding the application of remote sensing and digital technologies for assessing soil include:

- There are numerous studies investigating soil moisture via remote sensing. While soil moisture is not explicitly required in Alberta reclamation criteria (ESRD, 2013a, b), it could provide useful information regarding drainage on and off site.
- Erosion potential has been studied by utilizing remote sensing to assess bare ground cover. Bank stability, which is part of the Alberta reclamation criteria (ESRD, 2013a, b), can be assessed with remote sensing techniques.
- Measurements of soil stability are possible with remote sensing, but likely on scales that are not applicable to the reclamation assessment process in Alberta.
- Proximal soil sensors and/or reflectance spectroscopy may be more suitable for assessing soil properties, compared to aerial or spaceborne remote sensing (at the reclamation site scale), given spatial resolution limitations of aerial or spaceborne remote sensing. However, PSS are typically designed for agricultural applications, and therefore are more suitable to sites that can be accessed by vehicle; reflectance spectroscopy is also more suited to agricultural systems, or the collection of samples for processing in a laboratory. While PSS and reflectance spectroscopy may not be optimal for remote sites, they have the potential to reduce costs associated with sampling on many reclaimed sites (Degenhardt et al., 2014; Small & Underwood, 2015).

3.7 Water Bodies and Wetlands

Wetlands are discussed in this report, as they may be present on a forested or cultivated reclamation site; however, peatland reclamation criteria are not the focus of this report. C-CORE (2019) have performed an in-depth review of remote sensing technologies and their applicability to Alberta reclamation criteria for peatlands.

3.7.1 Review of EO/RS and Digital Technology Applications

Open water features and wetlands may be present on reclamation sites, both forested and cultivated, in Alberta. This section focuses on assessing water bodies and wetlands via remote sensing, with a focus on forested sites. Remote sensing has been used in river deltas and arctic regions of Canada to delineate open water features and assess hydraulic connectivity (Crasto et al., 2015; Pavelsky & Smith, 2008; Umbanhowar et al., 2013). Remote sensing technologies used in these studies included near-infrared satellite imagery, multispectral and panchromatic satellite imagery, and LiDAR. In general, remote sensing technologies provided good estimates of open water features; for example, Crasto et al. (2015) found that open water features were identified with over 95% accuracy.

In the boreal forest of Alberta, much research into large-scale wetland mapping has been conducted. Hird et al. (2017a) used LiDAR, optical imagery, radar, reference data, and existing wetland inventory to develop a machine-learning framework for predicting the probability of wetland occurrence in the study area (13,700 km^2). Using satellite-based SAR data, an analytical method which combined ascending/descending RADARSAT-2 image pairs and ancillary data was utilized to mitigate common errors with SAR data, resulting in over 99% accuracy when distinguishing water from land in Alberta's boreal forest (DeLancey et al., 2019a). DeLancey et al. (2019c) developed a framework for compiling numerous EO data sets (radar, optical, LiDAR), examining variables for their suitability in peatland modelling, optimizing the model, and predicting peatland occurrence over a large area (397,958 km^2); when compared to validation data, the peatland occurrence model had 87% accuracy. Recently, deep machine learning (specifically deep convolutional neural networks) has been applied to EO data (radar, DEMs) to predict wetland landcover classes over a 397,958 km^2 area with an overall accuracy of over 80% (DeLancey et al., 2019b).

There has been extensive assessment of boreal wetlands with remote sensing. Chasmer et al. (2020) conducted a review of boreal wetland remote sensing, with a focus on Canada. Wetland extent has been assessed via landcover classes (i.e., wetland versus upland), and can be narrowed down more specifically to wetland class (i.e., bog, fen, marsh, swamp), form/structure (i.e., graminoid, shrub, tree), and vegetation species; applicable technologies include air photos, multispectral, hyperspectral, and panchromatic imagery, SAR, shuttle imaging radar (SIR), and LiDAR (Chasmer et al., 2020). Ecosystem productivity (including biomass), vegetation structure, and habitat characterization are also possible (Chasmer et al., 2020). Moisture and water quality parameter such as soil moisture, water table, topography, water flux, water level, and water chemistry/turbidity can also be estimated with EO/RS technologies (Chasmer et al., 2020).

Aerial photography has been commonly used for interpretation of land cover and wetland class, vegetation form, and species identification (Chasmer et al., 2020). Hyperspectral imagery is typically used for detailed mapping of wetland class and form, species identification, productivity, and water properties. Multispectral data has been available for longer than technologies such as hyperspectral imagery, and therefore has been commonly used to determine landcover and wetland classes. SAR is particularly useful for assessing soil moisture, hydroperiod, and surface water extent. LiDAR can provide information on topography (other EO/RS technologies are of limited value in assessing topography due to interference by vegetation cover), landcover and wetland classification, vegetation structure, productivity, and water levels (Chasmer et al., 2020).

Chasmer et al. (2020) completed a detailed review of the accuracy of different remote sensing technologies for wetlands. This data can likely be extrapolated, at least in part, to upland systems. The accuracy of wetland extent, type, and attributes derived from remote sensing technologies varied greatly by the application and remote sensing system. More complex wetland attributes typically result in lower accuracy. Additionally, the way cover classes are defined impacts accuracy; for example, combining bogs and fens into the same class may improve accuracy.

When compared to field-collected data, high spatial resolution aerial photography, hyperspectral, and multispectral data had the highest average accuracies. However, wetland size impacts the resolution required for adequate accuracy; for example, Chasmer et al. (2020) found that large wetlands can be classified with medium-resolution data with 76% accuracy. The average accuracy of aerial photography was 80.5%. Hyperspectral accuracy varied by sensor, with the lowest average accuracy being 54.9% and highest being 90.2%. Satellite multispectral average accuracy varied from 54.9% to 88.0%. SAR average accuracy varied from 66.0% to 97.5% depending on the sensor. Airborne LiDAR had an average accuracy of 74.3%, while airborne multispectral LiDAR had an accuracy of 84.6%. It should be noted that there are complexities with the interpretation of this data set. For example, the sensors were used to evaluate different landscape and vegetation parameters. Combining remote sensing methods (i.e., optical imagery, SAR, and/or LiDAR) can significantly improve accuracy (Chasmer et al., 2020).

3.7.2 Considerations for Alberta Reclamation Criteria

Important considerations regarding the application of remote sensing and digital technologies for assessing water bodies and wetlands include:

- The Alberta reclamation criteria for forested and cultivated land (ESRD, 2013a, b), require assessment of drainage, ponding, and riparian functions. The EO/RS applications for wetlands discussed in Section 3.7.1 could likely be applied to these requirements.
- As with upland systems, multispectral and hyperspectral data are typically used to assess vegetation, while SAR and LiDAR are useful for assessing landscape and soil.
- As with upland systems, complex ecosystems tend to have lower accuracy; therefore, before applying EO/RS technologies, the complexity of the site should be considered.

3.8 Cultivated Lands and Agriculture

3.8.1 Review of EO/RS and Digital Technology Applications

Given that cultivated lands are very different from forested systems, and the availability of sensors affixed to farm equipment, digital technologies for cultivated lands have been assessed separately from other reclamation sites. Section 3.8 focuses predominantly on vegetation parameters. There are numerous applications for satellite- and drone-based remote sensing techniques in agriculture, especially as the practices of precision agriculture and smart farming become increasingly adopted. Precision agriculture utilizes GPS and machinery equipped with sensors and variable-rate apparatuses. For example, in Alberta, Faechner & Benard (2006) conducted a study using combine harvesters equipped with crop yield monitors and GPS systems to successfully map crop yields on reclaimed sites, and evaluated parameters that contributed to statistical confidence.

Beyond precision agriculture, smart farming looks to use advanced sensing and robotic technologies to increase yields and use resources in the most efficient manner (Inoue, 2020). While some of the more advanced hyperspectral techniques and drone-based technologies are not widely available for commercial use at this time, there are opportunities to use such technologies in the reclamation certification process. Inoue (2020) outlines smart farming-related information that can estimated by remote sensing, including parameters such as plant growth, water stress, weed infestation, and soil fertility, many of which are relevant to the Alberta reclamation certification process. A summary of remote sensing applications in agriculture can be found in Section 4.1.

In the United States and Europe, satellite-based remote sensing is used commercially to manage resources for farms ranging from approximately 5 to 20 ha (Inoue, 2020). FARMSTAR, a service in France, is used by farmers to optimize production of crops such as wheat and canola via remote sensing (Inoue, 2020). In Japan, large farm sizes and uniform crops make middle-resolution satellites operationally applicable (Inoue, 2020). Farm sizes in Alberta can be large (i.e., one quarter section is 65 ha), although the area requiring reclamation may be much smaller. Satellite-based remote sensing could be very applicable for monitoring reclamation criteria at agricultural sites in Alberta, but the size of the site should be considered to confirm whether a sensor has sufficient spatial and spectral solution.

Drone-based remote sensing offers higher resolution data acquisition and is a more flexible technology that can be applied at a smaller scale than satellite-based remote sensing. Additionally, drone-based assessment can be lower cost. Multispectral, thermal, and video-imaging modules were affixed to a drone and used to obtain data under varying conditions in Japan (Inoue, 2020). In the case study, various parameters could be assessed with the multispectral module: canopy and leaf chlorophyll content (CC-index, LC-index), canopy nitrogen content (CN-index), photosynthetic capacity (PC-index), head water content (HW-index), and soil carbon content (SC-index) (Inoue, 2020). Using infrared thermal data and micrometeorological data, the plant stress indicator (PS-index) was determined (Inoue, 2020). Lastly, 3D models of the land surface were created with video imagery and GPS data (Inoue, 2020). In this case study, the drone-based data was validated against field-collected data; hyperspectral datasets achieved higher statistical significance than the drone-based technology being tested, but the authors concluded that advanced drone-based remote sensing would be useful for monitoring crops, invasive species, diseases, and soil, especially on farms approximately 100 ha in size (Inoue, 2020).

While the use of UAVs (i.e., drones) is not currently common practice in agriculture, much research has been conducted to determine what sort of information can be gained from such technologies. At this time, UAV technology would be more suitable to enhancing reclamation certification assessments on cultivated land than large scale commercial application by farmers. Maes & Steppe (2018) state that remote sensing with UAVs can provide excellent spectral, spatial, and temporal resolution. Remote sensing with UAVs can be used in assessing vegetation height, nutrient status, plant vigour (including growth stage and biomass), drought stress, predicting yield, and detecting invasive species and disease (Maes & Steppe, 2018). As indicated by Inoue (2020), Maes & Steppe (2018) also suggest that RGB cameras, multispectral sensors, hyperspectral sensors, and thermal sensors can be used with UAVs. RGB cameras have high spatial resolution but low spectral resolution and can be used to develop vegetation indices, digital elevation models, and vegetation height maps (Maes & Steppe, 2018). Multispectral and hyperspectral sensors offer high spectral resolution and have been discussed in detail in section 3.1.

Thermal cameras are generally low resolution, and can be used to determine canopy temperature (Maes & Steppe, 2018).

Thermal imaging is particularly useful in assessing moisture/drought stress, as transpiration decreases the temperature of plant leaves (Maes & Steppe, 2018); often, this method makes use of the crop water stress index (CWSI). Recent research has used hyperspectral sensors to assess plant water status as sun-induced fluorescence (SIF), but this is a very new technique (Zarco-Tejada et al., 2012). It should be noted that utilizing UAVs with thermal sensors to assess plant water status is typical of orchards, due to the types of irrigation systems used. In a reclamation setting, this type of information would be useful in understanding plant water status at a site but would not have the same applications as in precision agriculture.

RGB sensors have been used successfully to map disease and insect severity in agriculture (Hunt & Rondon, 2017; Sugiura et al., 2016; Tetila et al., 2017). Drone-based multispectral imaging has been used for early disease detection, but may produce a large number of false-negatives (Albetis et al., 2017; Garcia-Ruiz et al., 2013). Hyperspectral imaging can be used for early detection and to identify different pathogens (although differentiation between pathogens has not been applied to UAVs) (Maes & Steppe, 2018). Hyperspectral and thermal data can complement one another.

Weed detection with satellite-based remote sensing was discussed in section 3.1.3. Maes & Steppe (2018) note that in UAV applications, spectral imagery and RGB cameras can be used to map weeds, and while supervised classification can be used successfully, machine learning (i.e., based on ground truthing data) offers a faster method of mapping weeds. UAVs can be used to detect weeds in row crops shortly after germination, utilizing modified RGB cameras and object-based imagery analysis (analysis based on objects rather than pixels) – this method requires high resolution imagery (Maes & Steppe, 2018).

Variable rate sensors, along with ground-based spectrometers, are currently used in precision agriculture, typically using multispectral sensors installed on tractors or sprayers to provide real-time variable fertilizer rates (Ali et al., 2017; Mulla, 2013). UAV studies have built on this concept, although not always with successful results (Hunt et al., 2018; Schirrmann et al., 2016). Hyperspectral imagery has been used (Franceschini et al, 2017;(Domingues Franceschini et al., 2017) Liu et al., 2017), and combined with thermal data (Elarab et al., 2015; Maimaitijiang et al., 2017), which could provide better results. However, this area of research is still relatively new. Application of such technologies for reclamation assessments is not applicable at this time.

Variation in growth stage and biomass within a field could provide useful information for reclamation practitioners in terms of areas requiring further reclamation or remediation prior to certification. Crop growth stage can be estimated using UAV-based RGB imagery (Maes & Steppe, 2018). Vegetation height can be estimated with UAV-based RGB imagery, and is a good indicator of actual height in cereal crops (Maes & Steppe, 2018); however, if the soil cannot easily be viewed, then UAV-based LiDAR imagery is more suitable (Maes & Steppe, 2018). Aboveground biomass can be estimated from vegetation indices derived from multispectral data (Maes & Steppe, 2018).

While lodging and yield predictions can be assessed with UAV-based sensors, these applications are not highly relevant to the reclamation certification process and are not discussed in detail in this report.

Drainage in agricultural fields can be assessed with remote sensing technologies. For example, in Ottawa, three drainage classes were identified in an agricultural field via expert observation. The observed drainage compared well with classified drainage based on airborne hyperspectral imagery (kappa coefficient = 0.68), there was moderate agreement with SAR-based classification (kappa coefficient = 0.58), and only fair agreement with a GPS-derived DEM (kappa coefficient = 0.31) (Liu et al., 2008). Onsite and offsite drainage assessments are required in reclamation assessments in Alberta; the hyperspectral technique described here, as well as techniques descried in section 3.5 to 3.7, may be applicable to the reclamation certification process.

3.8.2 Considerations for Alberta Reclamation Criteria

Important considerations regarding the application of remote sensing and digital technologies for assessing cultivated lands include:

- There are digital technologies applicable to cultivated land that may not be relevant to forested lands. For example, sensors (including variable rate sensors) affixed to farm equipment, as well as proximal soil sensors and reflectance spectroscopy (Sections 3.6.1.1 and 3.6.1.2) are well suited to monitoring vegetation and soils on cultivated land.
- While EO/RS technologies for cultivated land are typically described in terms of crop management, sensors are capable of monitoring vegetation health, biomass, height, growth stage, and invasive species, all of which are relevant to Alberta reclamation criteria for cultivated land.

4.0 SUMMARY

4.1 Environmental Parameters and Applicable Sensors

The key findings of the literature review are summarized in Table 2 and Table 3. Table 2 focuses mainly on forested systems, while Table 3 focuses on agricultural systems. It should be noted that there are a multitude of sensors and platforms that allow for digital assessment and measurement of the environment, at varying stages of technological development. This report has evaluated the most frequently used systems, as these are most likely to be applicable to reclamation sites in Alberta at this time. However, there are other sensors (such as colour-infrared, spaceborne imaging radar, and polarimetric and interferometric SAR) which are not discussed in detail but should be considered when planning a digital reclamation assessment program. The summary tables in this section focus on the most commonly used RS/EO and digital technologies.

It should also be noted that this report has not evaluated specific satellites or information systems, but there is a vast amount of information in the literature on such topics (i.e., Chasmer et al., 2020). While the accuracy of remote sensing and digital technologies can vary greatly given the area being assessed and technology used, McKenna et al. (2020) reported an average overall mapping accuracy of 84% in a review of remote sensing applications for assessment of mining impacts. Remote sensing and digital technologies have the potential to vastly reduce time and costs associated with environmental monitoring. For example in a sagebrush steppe ecosystem in the United States, Breckenridge et al. (2012) found remote sensing techniques took 22% of the time that point-frame field sampling would have taken.

Table 2. A summary of remote sensing and digital technology applications which may be applicable to reclamation sites, forested lands, and wetlands.
The table was largely adapted from Lechner et al. (2020). Information specific to wetlands and water was adapted from Chasmer et al. (2020). Information from the following sources has also been included: Mohamed et al. (2018), Payne et al. (2018), Robichaud et al. (2020), and Sorenson et al. (2018).

Diagnostic Parameter	Indicators	Applicable Sensors
Land use/land cover	Land use/land cover	Multispectral-fine, multispectral-med, hyperspectral, SAR, SIR LiDAR
Vegetation cover	Vegetation and bare ground cover	Multispectral-fine, multispectral-med, hyperspectral*, SAR, LiDAR
	Foliage projective cover	Multispectral-fine, multispectral-med, hyperspectral*, SAR, LiDAR
	Tree density	Multispectral-fine, multispectral-med, hyperspectral*, SAR, LiDAR
	Coarse woody debris	Multispectral-fine, multispectral-med, hyperspectral*, SAR, LiDAR
	Greenness	Multispectral-fine, multispectral-med, hyperspectral*, SAR, LiDAR
	Vegetation health	Multispectral-fine, multispectral-med, hyperspectral, SAR, LiDAR
	Wetland class, wetland form/structure	Multispectral, hyperspectral, SAR, SIR, LiDAR
Vegetation structure	Tree height	Multispectral-fine*, LiDAR
	Vertical forest structure	SAR*, LiDAR
	Aboveground biomass	Multispectral-fine, multispectral-med, hyperspectral, SAR, LiDAR
	Leaf area index (LAI)	Multispectral-fine, multispectral-med, hyperspectral, SAR, LiDAR
	Basal area	Multispectral-fine, multispectral-med, hyperspectral, SAR, LiDAR
	Crowns and gap sizes	Multispectral-fine, LiDAR
Vegetation chemistry and moisture	Foliar chemistry	Multispectral-fine*, multispectral-med*, hyperspectral
	Fraction of absorbed photosynthetically active radiation	Multispectral-fine, multispectral-med, hyperspectral, SAR, LiDAR
	Moisture content	Multispectral-fine*, multispectral-med, hyperspectral, SAR
Biodiversity	Identification of individual species	Multispectral-fine, multispectral-med, hyperspectral, LiDAR
	Biodiversity measures (i.e., alpha, beta)	Multispectral-fine, multispectral-med, hyperspectral, LiDAR
Disturbance	Forest/vegetation disturbance and recovery over multiple years	Multispectral-fine, multispectral-med, hyperspectral*, SAR
	Reclamation	Multispectral, hyperspectral, SAR, LiDAR
	Fire scarring (visibly blackened land due to fire occurrence)/fire effects	Multispectral-fine, multispectral-med, hyperspectral, SAR, LiDAR
Topography	Elevation/slope	LiDAR, SAR (especially InSAR)
	Topographic variability	

Diagnostic Parameter	Indicators	Applicable Sensors
Soil	Soil type	Multispectral-fine*, multispectral-med*, hyperspectral, SAR, reflectance spectroscopy*
	Soil moisture	Multispectral-fine, multispectral-med, hyperspectral, SAR, reflectance spectroscopy*, PSS*
	Soil properties (i.e., pH, electrical conductivity, organic carbon, nitrogen)	Hyperspectral, SAR, reflectance spectroscopy*, PSS*
	Erosion	Multispectral-fine, multispectral-med, hyperspectral*, SAR, LiDAR
	Bank stability	Multispectral, colour-infrared, and panchromatic
Water	Water level/extent	Multispectral, SAR, SIR, LiDAR
	Bathymetry	
	Water chemistry	Multispectral, hyperspectral

InSAR = interferometric synthetic aperture radar
Light ranging and detection (LiDAR) refers largely to airborne platforms
Multispectral-fine = multispectral sensors with fine spatial resolution
Multispectral-med = multispectral sensors with medium to coarse spatial resolution
Multispectral = the level of resolution was not specified
PSS = proximal soil sensors
SAR = synthetic aperture radar
SIR = spaceborne imaging radar
* denotes a less common application for the indicator

Because agricultural systems can be quite different than forested and wetland ecosystems, applicable digital technologies have been summarized separately in Table 3. It should be noted that the technologies described are relevant to reclamation sites intended for agricultural land use, and many of the technologies could be used to assess reclamation certification criteria.

Table 3. A summary of different remote sensing and digital technology applications which may be applicable to cultivated land.
The table was adapted Inoue (2020), Maes & Steppe (2018), and Sorenson et al. (2018).

Diagnostic Parameter	Indicators	Applicable Sensors
Phenology	Heading, maturity, growing season length	Multispectral/hyperspectral, SAR
Growth	Biomass leaf area index (LAI), yield, growth stage, canopy height and biomass	Multispectral/hyperspectral, SAR, RGB-camera (for growth stage, height, and biomass), LiDAR
Water stress	Water content, stress index, detection in early stages	Multispectral/hyperspectral, TIR
Photosynthetic activity	Chlorophyll content, fraction of photosynthetically active radiation	Multispectral/hyperspectral, TIR
Nutrient status	Nitrogen, phosphorus	Multispectral/hyperspectral (and RGB-camera and TIR, although less suited)
Grain quality	Protein and water content	Multispectral/hyperspectral
Lodging	Damage degree	Multispectral/hyperspectral

Diagnostic Parameter	Indicators	Applicable Sensors
Disease/insect infestation	Symptoms, damage degree, severity of infection	Multispectral/hyperspectral, TIR, RGB-camera
Weed infestation	Distribution, growth	Multispectral/hyperspectral, RGB-camera (object based)
Soil fertility	Soil humus (carbon) content	Multispectral/hyperspectral, reflectance spectroscopy*, PSS*
Drought	Soil water content	Multispectral/hyperspectral, SAR, TIR, reflectance spectroscopy*, PSS*
Surface irregularity	3D surface model (i.e., DEM, DSM, DTM)	Multispectral, RGB-camera

DEM = digital elevation model
DSM = digital surface model
DTM = digital terrain model
InSAR = interferometric synthetic aperture radar
LiDAR = light ranging and detection
PSS = proximal soil sensors
Multispectral = the level of resolution was not specified
SAR = synthetic aperture radar
SIR = spaceborne imaging radar
TIR = thermal infrared sensor
* denotes a less common application for the indicator

4.2 Application to Alberta Reclamation Criteria

Section 4.1 provided a detailed summary of which sensors should be considered when measuring different environmental parameters with digital technologies. When considering the site-based application of remote sensing to support the reclamation certification process in Alberta, the spatial resolution, revisit frequency, and spectral configuration of the sensor and platform must be considered. Reclamation sites may vary in size, and this affects which technologies are most appropriate for site assessment. For example, operationally available remote sensing systems can provide data at resolutions <1 m to >1 km (C-CORE, 2019). Satellite-based sensors applicable to reclamation have spatial resolutions ranging from 0.5 m to 10 m, with image widths ranging from >15 km to >250 km (C-CORE, 2019).

If using satellite-based technologies, temporal data acquisition is limited to the revisit frequency of the satellite, however many EO sensors have weekly and even daily revisit frequencies. Airborne and UAV technologies can be heavily dependent on weather and scheduling factors. Additionally, the spectral configuration (i.e., the number of bands used by optical sensors, or the types of wavelengths used in SAR and LiDAR) determines the type of information that can be collected (i.e., overstory versus understory parameters). Reclamation sites may be small (i.e., 1 ha) or very large (i.e., 100 to 1,500 ha) (Rochdi et al., 2014), and therefore some sensors will be able to provide suitable resolution while others will not.

Spaceborne optical sensors (panchromatic and multispectral) and SAR appear to be operationally available, as well as airborne optical sensors (panchromatic, multispectral, and hyperspectral) (C-CORE, 2019). Much of the literature regarding EO/RS technologies for monitoring vegetation focuses on multispectral and hyperspectral sensors, with SAR and LiDAR being discussed in more recent papers. As technology continues to progress, hyperspectral analysis will likely become more widely used and more operationally feasible for reclamation. At present, LiDAR is considered an expensive technology (Rochdi et al., 2014), primarily used for assessing landscape features and terrain. However, the literature suggests that it holds promise for assessing vegetation structure, which may lead to increased cost-effectiveness in the future.

In a recent study, C-CORE (2019) evaluated airborne panchromatic, multispectral, and hyperspectral sensors, along with satellite-based panchromatic, multispectral, and SAR sensors, for their ability to address peatland (Alberta Environment and Parks, 2017) and forested (ESRD, 2013b) reclamation criteria in Alberta. Hyperspectral sensors were only evaluated for airborne platforms, as the authors stated the technology is not available on an operational basis for spaceborne platforms (C-CORE, 2019); however, the current literature review indicates that there are numerous hyperspectral sensors available, indicating that operational availability is on the horizon. The authors evaluated the technologies based on technology readiness levels (TRLs), which ranged from (0) hypothetical concept to (7) field proven (C-CORE, 2019). C-CORE (2019) then rated the technologies as either not applicable, potentially applicable (TRL 0 to 4), or applicable (TRL 5 to 7) to the Alberta reclamation certification process. The findings of C-CORE (2019) have been summarized in Tables 4 to 7, along with information from the current literature review, to assess the applicability of digital technologies to address specific Alberta reclamation assessment criteria for forested and cultivated lands (ESRD, 2013a, b).

Table 4. Alberta reclamation landscape assessment parameters for forested and cultivated lands, with consideration of applicable digital technologies as described in C-CORE (2019) and the current report.

Reclamation Certification Parameter	C-CORE (2019) Alberta Forested Lands Assessment – Summary	Current Literature Review Comments (Forested)	Current Literature Review Comments (Cultivated)*
Drainage – Surface Water Flow (Onsite/Offsite)	• Applicable: airborne PAN, MS • Potentially applicable: HS, satellite PAN, MS • Not applicable: SAR	• Near-infrared satellite imagery, MS and PAN satellite imagery, and LiDAR may be applicable	• Techniques used in forested land may also be adapted to cultivated land
Drainage – Ponding	• Applicable: HS, airborne and satellite PAN, MS • Potentially applicable: SAR	• MS, SAR, SIR, LiDAR to assess wetland water level and extent in literature	• Techniques used in forested land may also be applicable on cultivated land • HS used by researchers
Riparian Functions – Bank or Shore Stability	• Potentially applicable: HS, airborne and satellite PAN and MS, SAR	• PAN, MS, and colour-infrared along riverbanks in literature	• PAN, MS, and colour-infrared along riverbanks in literature
Water Erosion – Gullying	• Applicable: airborne and satellite PAN, airborne MS • Potentially applicable: HS, satellite MS • Not applicable: SAR	• MS, HS, SAR, and LiDAR used to assess erosion in literature • PAN and MS to assess erosion potential based on bare ground cover in literature	• Techniques used in forested land may also be applicable on cultivated land
Water Erosion – Rilling pedestaling, fans	• Applicable: airborne and satellite PAN, airborne MS	• MS, HS, SAR, and LiDAR used to assess erosion in literature	• Techniques used in forested land may also

Reclamation Certification Parameter	C-CORE (2019) Alberta Forested Lands Assessment – Summary	Current Literature Review Comments (Forested)	Current Literature Review Comments (Cultivated)*
	• Potentially applicable: HS, satellite MS • Not applicable: SAR	• Researchers have used PAN and MS to assess erosion potential based on bare ground cover	be applicable on cultivated land
Wind Erosion	• Potentially applicable: HS, airborne and satellite PAN and MS • Not applicable: SAR	• MS, HS, SAR, and LiDAR used to assess erosion in literature • Researchers have used PAN and MS to assess erosion potential based on bare ground cover	• Techniques used in forested land may also be applicable on cultivated land
Soil Stability – Slumping/Wasting	• Applicable: airborne and satellite PAN, airborne MS • Potentially applicable: HS, satellite MS, SAR	• InSAR typically used to assess soil stability	• InSAR typically used to assess soil stability
Soil Stability – Subsidence	• Applicable: SAR • Potentially applicable: airborne and satellite PAN, MS • Not applicable: HS	• InSAR typically used to assess soil stability	• InSAR typically used to assess soil stability
Bare Areas	• Applicable: airborne and satellite PAN and MS, HS • Potentially applicable: SAR	• PAN, MS, HS appear to be commonly used	• Techniques used in forested land may also be applicable on cultivated land
Operability – Micro-Contour	• Potentially applicable: airborne and satellite PAN • Not applicable: airborne and satellite MS, HS, SAR	• Cultivated land techniques may be applicable if sparse vegetation cover	• MS and RGB cited in literature for assessing surface irregularity
Operability – Meso- and Macro-Contour	• Applicable: airborne and satellite PAN and MS, HS • Potentially applicable: SAR	• LiDAR, SAR, InSAR, PolInSAR cited by researchers for assessing elevation and slope, although often on scales larger than a single site	• MS and RGB cited in literature for assessing surface irregularity
Operability – Gravel and Rock	• Applicable: airborne and satellite PAN and MS, HS • Potentially applicable: SAR	• Texture and coarse fragments assessed using MS, however scale likely not appropriate for reclamation sites; sparse vegetation improves measurement	• Texture and coarse fragments assessed using MS, however scale likely not appropriate for reclamation sites; sparse vegetation improves measurement

Reclamation Certification Parameter	C-CORE (2019) Alberta Forested Lands Assessment – Summary	Current Literature Review Comments (Forested)	Current Literature Review Comments (Cultivated)*
		• Reflectance spectroscopy and PSS could be applicable	• Reflectance spectroscopy and PSS could be applicable
Debris – Woody/Organic Debris	• Potentially applicable: airborne and satellite PAN and MS, HS • Not applicable: SAR	• MS, SAR, and LiDAR have been used by researchers	• Techniques used in forested land may also be applicable on cultivated land
Debris – Industrial and Domestic Refuse	• Applicable: airborne and satellite PAN, airborne MS • Potentially applicable: HS, satellite MS, SAR	• Could potentially use land cover classes based on MS or PAN	• Could potentially use land cover classes based on MS or PAN

* When information specific to cultivated land not found, information from forested and grassland areas considered.
HS = hyperspectral
LiDAR = light detection and ranging
MS = multispectral
PAN = panchromatic
PollnSAR = polarimetric Interferometry SAR
PSS = proximal soil sensors
RGB = red, green, blue wavelength sensors
SAR = synthetic aperture radar
SIR = shuttle imaging radar
Note that C-CORE (2019) only evaluated airborne hyperspectral (HS) platforms and spaceborne SAR platforms.

Table 5. Alberta reclamation soil assessment parameters for forested and cultivated lands, with consideration of applicable digital technologies as described in C-CORE (2019) and the current report.

Reclamation Certification Parameter	C-CORE (2019) Alberta Forested Lands Assessment – Summary	Current Literature Review Comments (Forested)	Current Literature Review Comments (Cultivated)*
Soil Disturbance	• Applicable: airborne and satellite PAN and MS, HS • Potentially applicable: SAR	• MS and HS likely applicable (land use mapping)	• MS and HS likely applicable (land use mapping)
Surface Characteristics (Topsoil Depth/Distribution)	• PAN and MS, HS, SAR considered not applicable	• Sensors using X, C, L, and P band microwaves (i.e., radar) can penetrate soil (i.e., P bands may penetrate 50 cm into soil), although typically used for moisture measurements and unclear if suitable for measuring soil depth; spatial resolution not suitable to site-scale	• Sensors using X, C, L, and P band microwaves (i.e., radar) can penetrate soil (i.e., P bands may penetrate 50 cm into soil), although typically used for moisture measurements and unclear if suitable for measuring soil depth; spatial resolution not suitable to site-scale
Operability – Meso-Contour, Micro-Contour, Surface Stoniness, Coarse Fragment Content (Cultivated Lands Only)	• Not included in assessment	• N/A	• MS and RGB cited in literature for assessing surface irregularity
Topsoil Colour (Cultivated Lands Only)	• Not included in assessment	• N/A	• HS, MS, and RGB sensors used but likely not application at the site-scale
Vertical Processes – Soil Texture	• Potentially applicable: airborne and satellite MS, HS, SAR • Not applicable: airborne and satellite PAN	• SAR has potential given ability for microwaves to penetrate soil, but unsuitable spatial resolution • MS and HS also cited in the literature • PSS (if vehicle accessible) • Reflectance spectroscopy	• SAR has potential given ability for microwaves to penetrate soil, but unsuitable spatial resolution • PSS • Variable rate sensors • Reflectance spectroscopy
Vertical Processes – Consistence and Structure	• PAN and MS, HS, SAR considered not applicable	• Strong evidence not found in the literature	• Strong evidence not found in the literature

Reclamation Certification Parameter	C-CORE (2019) Alberta Forested Lands Assessment – Summary	Current Literature Review Comments (Forested)	Current Literature Review Comments (Cultivated)*
Vertical Processes – Rooting Restrictions	• PAN, MS, HS, SAR considered potentially applicable	• May be possible to infer from remote sensed soil moisture and land cover classes (SAR, MS most likely applicable)	• May be possible to infer from remote sensed soil moisture and land cover classes (SAR, MS most likely applicable)
Level 2 Soil Assessment	• PAN, MS, HS, SAR considered not applicable	• PSS (if vehicle accessible) • Reflectance spectroscopy	• PSS • Variable rate sensors • Reflectance spectroscopy • HS and SAR cited in literature

* When information specific to cultivated land not found, information from forested and grassland areas considered.
HS = hyperspectral
MS = multispectral
PAN = panchromatic
RGB = red, green, blue wavelength sensors
SAR = synthetic aperture radar
SIR = shuttle imaging radar
PSS = proximal soil sensor
Note that C-CORE (2019) only evaluated airborne hyperspectral (HS) platforms and spaceborne SAR platforms.

Table 6. Alberta reclamation vegetation assessment parameters for forested lands, with consideration of applicable digital technologies as described in C-CORE (2019) and the current report.

Reclamation Certification Parameter	C-CORE (2019) Alberta Forested Lands Assessment – Summary	Current Literature Review Comments
Desired Plants – Woody Species	• Applicable: airborne PAN and MS, HS • Potentially applicable: satellite PAN and MS • Not applicable: SAR	• MS used to delineate vegetation classes • HS used to identify species • LiDAR, PPC, RGB sensors, SAR for vegetation structure (i.e., density, height)
Desired Plants – Herbaceous Species	• Potentially applicable: HS • Not applicable: airborne and satellite PAN and MS, SAR	• MS used to delineate vegetation classes • HS used to identify species
Quantity – Production	• Applicable: airborne PAN and MS • Potentially applicable: HS, satellite PAN and MS • Not applicable: SAR	• Biomass measured with MS and • forest biomass measured with SAR and LiDAR (spaceborne platforms more accurate when biomass higher)
Quality – Plant Growth, Development	• Applicable: airborne and satellite MS, HS • Potentially applicable: airborne and satellite PAN • Not applicable: SAR	• Vegetation indices developed with MS and HS data applicable
Quality – Limitations Affecting Vegetation	• Applicable: airborne and satellite MS, HS • Potentially applicable: airborne and satellite PAN • Not applicable: SAR	• TIR used in agricultural systems for assessing drought stress (potential to apply to forested communities)
Weeds/Undesirable Plants	• Applicable: HS • Potentially applicable: airborne and satellite MS • Not applicable: airborne and satellite PAN, SAR	• HS commonly used
Litter and LFH	• PAN, MS, HS, SAR considered not applicable	• Unlikely to be suitable for remote sensing technologies

HS = hyperspectral
LFH = litter, fibric, humic
LiDAR = light detection and ranging
MS = multispectral
PAN = panchromatic
PPC = photogrammetric point clouds
RGB = red, green, blue wavelength sensors
SAR = synthetic aperture radar
TIR = thermal infrared
Note that C-CORE (2019) only evaluated airborne hyperspectral (HS) platforms and spaceborne SAR platforms.

Table 7. Alberta reclamation vegetation assessment parameters for cultivated lands, with consideration of applicable digital technologies as described in the current report.

Reclamation Certification Parameter	Current Literature Review Comments
Crop Type	• Likely would not need to be assessed via digital technologies • Aerial photos likely sufficient
Growth Stage	• RGB sensors (droned-based) are suitable
Plant Height	• RGB sensors (droned-based) are suitable • LiDAR (droned-based) if ground not visible
Plant Density	• RGB and LiDAR (drone-based) have been used in forested systems and may be applicable
Head/Tuber Length	• Unlikely to be suitable for remote sensing technologies
Head/Pod/Tuber Weight	• Unlikely to be suitable for remote sensing technologies
Plant Health	• TIR has been used to develop crop stress indices and assess drought stress • Variable rate sensors can be used to monitor nutrient status (i.e., nitrogen), and MS sensors to assess leaf nitrogen, chlorophyll content, and photosynthetic capacity • RGB, MS, and HS sensors have been used to assess crop disease extent (drone-based), although not always with sufficient accuracy • RGB and MS sensors are suitable for developing vegetation indices (i.e., NDVI) which assess plant health as greenness
Seed Development	• Unlikely to be suitable for remote sensing technologies
Pod Density	• Unlikely to be suitable for remote sensing technologies
Litter Quantity	• Unlikely to be suitable for remote sensing technologies
Weeds and Undesirable Plants	• MS, HS, and RGB sensors

HS = hyperspectral
LiDAR = light detection and ranging
MS = multispectral
NDVI = normalized difference vegetation index
RGB = red, green, blue wavelength sensors
SAR = synthetic aperture radar
TIR = thermal infrared

5.0 CONCLUSIONS

Remote sensing and digital technologies are becoming increasingly popular for mapping and assessing reclamation and ecological processes. While land cover mapping is one of the most common uses of remote sensing data (McKenna et al., 2020), complex topics have been studied in more recent years, such as ecosystem function and species composition. There are numerous digital technologies available for forested and cultivated lands. Some of the available technologies are ready to be applied for operational monitoring, whereas others have been studied experimentally and require further validation. Of the passive sensors, optical sensors (RGB, panchromatic, multispectral, and hyperspectral) are commonly used. SAR and LiDAR are commonly used active sensors. Common sensor platforms include spaceborne (i.e., satellite), airborne (i.e., aircraft, helicopter), and ground-based (i.e., UAVs). On cultivated lands, sensors can be affixed to farm equipment, providing monitoring of vegetation and soil.

When applying EO/RS and digital technologies to assess reclamation criteria for forested and cultivated land in Alberta, the spatial resolution, revisit frequency, and spectral configuration of the sensor and platform must be considered. Depending on the size of the reclamation site, different spatial and spectral resolutions may be required to obtain an acceptable degree of accuracy. The revisit frequency of the sensor/platform should be considered depending on the goals of the project (i.e., temporal monitoring may require more frequent visits). Additionally, different sensors are suitable for capturing different environmental data.

The literature review revealed numerous applications of digital technologies that are directly applicable to reclamation criteria and monitoring in Alberta. Digital technologies have the potential to be used to supplement in-field data collection, however it should be noted that in most cases, the application of digital technologies will require in-field data collection as validation.

There are potential significant cost savings associated with the utilization of digital technologies to augment traditional reclamation assessments, such as reduced field sampling or reduced laboratory analysis. An understanding of the cost savings associated with EO/RS data collection would help to improve adoption of these technologies in reclamation (De Abreu et al., 2015). There are opportunities to capitalize on the recent advances in remote sensing and digital technologies to enhance the reclamation certification process in Alberta.

PART 2: REVIEW OF TECHNOLOGIES USED BY REGULATORY ORGANIZATIONS FOR RECLAMATION CERTIFICATION

6.0 INTRODUCTION

Recently drafted Alberta Directives for Reclamation Certification Site Assessment for Pits and Quarries in Cultivated and Forested Lands enable the use of new technology-based data collection to augment in-field assessments. Earth observations (EO), remote sensing (RS), and other digital technologies are emerging as useful tools for monitoring the environment and collecting environmental data. From an environmental perspective, EO/RS data are primarily used in mapping and detecting changes in the environment, and for monitoring (Powter et al., 2016).

The objective of this report was to determine if and how government and regulatory organizations in Canada, Australia and the United States of America have incorporated technology-based data collection for the purposes of monitoring land reclaimed after industrial disturbances such as mining, gravel extraction and oil and gas well drilling. Information contained in this report may help inform future policies and guidance for regulatory decisions on the use of technology-based data collection for reclamation certification in Alberta.

7.0 METHODS

A search of government regulations or guidance documents as well as news articles, workshop reports, and scientific reports and papers was completed. Searches were completed for Canada, Australia, and the United States of America. The focus was on reclamation certification or monitoring using EO and RS, but other environmental monitoring and data collection technologies that could be applicable to, or are very similar to reclamation monitoring, was also considered in scope for the literature review.

Key search terms included:

- Remote sensing
- Drone
- UAV (Unmanned Aerial Vehicle)/UAS (Unmanned Aircraft System)
- LiDAR
- RADAR
- (Mine) reclamation
- (Mine) rehabilitation
- Regulation
- Relevant jurisdictions (Queensland, Saskatchewan, USA, etc.)
- Satellite
- Aerial imagery

Terms were often combined in the searches, for example: “remote sensing mine rehabilitation Queensland”.

Results of the review are presented in Section 3.0, which is organized into the three main jurisdictions searched: Canada, Australia, and the United States of America. Within each jurisdiction, applications are split into relevant reclamation applications and regulatory applications in other industries that are highly relevant to reclamation. Ongoing development of technologies are also presented, particularly if few current regulatory applications were found.

8.0 RESULTS AND DISCUSSION

8.1 Canada

8.1.1 Reclamation

The following are examples of regulatory use of EO and RS for reclamation monitoring or certification in Canada:

- *Guidelines for the Closure and Reclamation of Advanced Mineral Exploration and Mine Sites in the Northwest Territories* (Mackenzie Valley Land and Water Board & Aboriginal Affairs and Northern Development Canada, 2013), handed down by the federal government, promotes "passive monitoring" where access to the entire site may be difficult. These passive techniques refer to remote sensing, and these are intended to be applied for monitoring vegetation, and soil and geotechnical stability. No specifics on remote sensing methods are provided.

- The Saskatchewan Research Council (SRC), a government research and development agency, provides remote sensing analysis as part of their science expertise to industry for reclamation or restoration purposes (SRC, n.d. a). In other words, they have built capacity to aid industry in the use of these technologies for reclamation. Additionally, the SRC offers UAV services for various projects and tasks, such as revegetation assessments and monitoring, and mine monitoring and site inspections to meet regulatory requirements (Saskatchewan Research Council, n.d. b). This suggests that remote sensing is in demand in Saskatchewan and already serves a regulatory purpose.

- In Alberta, the 2018 *Conservation and Reclamation Directive for Renewable Energy Operations* (Alberta Environment and Parks, 2018) encourages the use of remote sensing technology for a variety of purposes, including: desktop review assessment, pre-disturbance site vegetation assessment, and reclamation certificate site vegetation assessment. In addition, use of the Landscape Analysis Tool (LAT), a geospatial product for assessing nearby features of interest based on aerial imagery and other government data, is required.

  Some highlighted examples of uses of remote sensing data in the *Conservation and Reclamation Directive for Renewable Energy Operations* include:

    - Digital Elevation Models (DEM) from LiDAR data for topography mapping
    - Assessing plant health and productivity using indices like NDVI to compare between disturbed and undisturbed sites
    - Assessing changes in vegetation over time with multiple images over multiple time periods and using stereoimagery or LiDAR to measure plant height and growth.

  A few particulars for remote sensing data are laid out in the *Conservation and Reclamation Directive for Renewable Energy Operations*, including:

  - Out of four years of vegetation assessments required for reclamation monitoring, two may be conducted entirely remotely. The other two must include ground measurements.
  - A maximum spatial resolution of 10 m, but often smaller depending on the technology employed
  - Geospatial data must be in an approved file format, with UTM NAD 83 coordinates and metadata
  - Data must be provided with an open government license

- In 2014, *Monitoring Procedures for Wellsite, In-Situ Oil Sands and Coal Mine Reclamation in Alberta* (MOPRA) (Rodshi et al., 2014) was released. Development of these procedures was funded, in part, by Alberta Environment and Sustainable Resources Development. The goal of developing these procedures was to provide a consistent method for using remote sensing techniques in reclamation monitoring, with a caveat that further research is still needed to verify the approach for broader applicability to different ecosite types. MOPRA used LiDAR, multispectral and hyperspectral data to determine land cover change, canopy height, fractional cover, tree species and canopy leaf area index to examine vegetation regrowth on wellsites.

- In 2015 a workshop on applying remote sensing technology for regulatory purposes and how to move forward was held with Natural Resources Canada (NRCAN), Alberta Energy Regulator (AER), and other participants from the Government of Alberta (De Abreu et al., 2015). Participants agreed that remote sensing has many uses, but there are impediments to operational implementation including determining if and how it can meet regulatory requirements for monitoring or assessment, cost of implementation and ability to obtain suitable resolution data, both temporally and spatially, and for multiple sensor types.

- In Alberta, a remote sensing approach for Detailed Site Assessments (DSAs), as per *Coal and Oil Sands Exploration Reclamation Requirements* (OSE Guidelines), was utilized for Imperial Oil Resources Ltd. in Cold Lake, AB (Wood Environment and Infrastructure Solutions, 2020). The remote sensing approach was applied to 22 oil sands exploration wellsites and associated access roads. LiDAR with a resolution of 0.3 m, multispectral data with a resolution of 2 m, and panochromatic data with a resolution of 0.5 m, along with ground-truth data was utilized to derive land cover classes, woody species height and percent cover estimates and species diversity estimates. A reclamation certificate was issued by the Alberta Energy Regulator for the sites assessed using the remote sensing approach (Wood Environment and Infrastructure Solutions, 2020).

- Prior to 2010, mines in BC were piloting remote sensing technology for vegetation assessments, including classifying vegetation groups (Straker et al., 2009, Straker et al., 2004).

8.1.2 Forestry and Other Industries

The following are examples of regulatory use of EO and RS for forestry planning and surveys in Canada:

- In BC, the 2020 silviculture manual *Silviculture Surveys Procedures Manual: Regen Delay, Stocking and Free Growing Surveys Plus Alternative Survey Methodologies* (B.C. Ministry of Forests, Lands, Natural Resource Operations and Rural Development, 2020) includes remote sensing technologies such as LiDAR and platforms such as UAVs as potential methods for conducting forest inventories, terrain modeling, vegetation mapping, forest health, and silviculture surveys. Benefits included are increased safety (fewer people in the field in potentially dangerous situations), and time and money savings in conducting surveys; however, ground truthing is still required.

- The Manitoba government recognizes the benefits of remote sensing in forestry in their silviculture manual. LiDAR and UAVs are mentioned for their potential to map topography and measure tree heights; however, no specific details are provided and use of these technologies was in the trial stage (Manitoba Ministry of Sustainable Development, 2016).

- In Alberta, there has even been research into the use of remote surveys for highly detailed seedling counts required for silvicultural regeneration surveys (Feduck et al., 2018).

- NRCan uses remote sensing largely to monitor forest fires, but also for other aspects of forest management, such as caribou habitat mapping (Natural Resources Canada, 2020).

- In 2019, the Canadian Space Agency launched the RADARSAT Constellation Mission (RCM), a constellation of 3 radar satellites which scan the entire country multiple times daily (Canadian Space Agency, 2020). This data is used by various federal departments to aid in their mandates and is freely available to other governments and the public, with some data restrictions (Canadian Space Agency, 2021; Canadian Space Agency, 2019a). Monitoring the environment is one of the chief purposes of these satellites, and intended applications include monitoring soil stability, determining surface soil moisture and related vegetation properties, monitoring forest regeneration and optimizing management, monitoring vegetation cover and changes, and supporting decision making in compliance programs (Canadian Space Agency, 2019b; Canadian Space Agency, 2019c).

All of these applications within forestry could be directly applicable to reclamation monitoring, particularly monitoring the health and cover of reclamation vegetation and recent plantings, but also terrain modeling and endangered species habitat modeling.

8.1.3 Summary

There appears to be a lot of development in remote sensing technologies and approaches to utilizing them, as well as collaboration on ideas, however, to date, there has been little regulatory application. So, while many agencies tout the benefits of remote sensing, the need to fill important knowledge gaps is highlighted, and ground truthing is often emphasized. Additionally, a standardized approach will be beneficial if explicit regulation is to occur.

A lot of development in the forestry industry can be easily applied to reclamation, so it may be useful for the other industries to look to forestry as an example for how to effectively incorporate remote sensing technology. Silviculture in particular has many similarities with reclamation monitoring, as both must consider the success of newly established plant growth on their sites.

The new RADARSAT Constellation Mission project also provides a unique opportunity for free remote sensing data that is collected daily. This will provide a wealth of regularly updated data that, aside from its other values in vegetation and landscape monitoring, will also help monitor changes in reclamation over time more frequently than typical land-based annual surveys.

8.2 Australia

8.2.1 Reclamation

The Commonwealth of Australia has a long history of coal and other mining (Commonwealth of Australia – Geoscience Australia, 2015, 2015; Roche & Judd, 2016; Kilvert, 2020). Mine reclamation is termed "rehabilitation" in Australia, and the federal level government is called the Commonwealth. Australia is comprised of six states and two territories; in the states, mining regulation is largely governed by the state governments while the Commonwealth provides additional guidance, whereas industry in the territories is governed more directly by the Commonwealth.

Commonwealth Government

Leading Practice Sustainable Development Program for the Mining Industry (Department of Industry, Innovation and Science Australia & Department of Foreign Affairs and Trade Australia, 2016) is a guidance document on mine reclamation created by Australia's Department of Industry, Innovation and Science, and cofounded by the Department of Foreign Affairs and Trade. This is the primary reference document in the Northern Territory (Northern Territory Government, 2020), and use as guidance by both regulators and operators is encouraged in the states.

In this document, remote sensing is highlighted as an important tool for assessing mine reclamation, and a few important technologies are detailed in brief:

- Aerial photography used with GIS to create spatial products like thematic maps, such as bare ground areas, can be applied towards monitoring and management decisions
- Specialized (yet widely available) satellite imagery that can be applied to standardized approaches like the Normalized Difference Vegetation Index (NDVI) may be used to assess vegetation health and cover
- Unmanned aerial vehicles (UAV) can be used to extrapolate ground-based survey data to larger areas within the reclaimed lands (i.e. turning point-based data into polygon-wide data) using high-resolution (8-10 cm resolution), aerial photographs, multispectral imagery and photogrammetry

This document also illustrates remote sensing applications through the case study of Curragh coal mine in Queensland. For this mine, UAVs have been employed in a variety of ways to aid reclamation monitoring. Aerial photographs and multispectral imagery collected by UAVs with a high resolution (8-10 cm) has been used to monitor landform stability and vegetation. UAV imagery and photogrammetry has been used to identify erosion hotspots and calculate the volume of soil loss or deposition, determine the presence of specific weed species, determine percent cover of various vegetation types and erosion areas, and create digital surface models of the reclaimed slope and aspect. UAV imagery is still complemented by ground-based surveys, but such surveys are expected to reduce over time as confidence in the remote sensing data increases (Department of Industry, Innovation and Science Australia & Department of Foreign Affairs and Trade Australia, 2016).

Conversely, LiDAR (Light Detection and Ranging), both airborne and ground-based (terrestrial), is highlighted as being underutilized, but promising uses include collecting quantitative and highly accurate structural characteristics of both landforms and vegetation (Department of Industry, Innovation and Science Australia & Department of Foreign Affairs and Trade Australia, 2016). However, recent closure plans from the Ranger Mine (Northern Territory) lease holder, Energy Resources of Australia Ltd. (ERA), initially released in 2018 and updated in 2019 and 2020, detailed an intent to used LiDAR to survey the final landform and monitor vegetation, but the Commonwealth government has requested more details on the specifics of how ERA intends to apply LiDAR, as well as a regular review of the technology to verify it is being used optimally (Australian Department of the Environment and Energy, 2018; Energy Resources of Australia Ltd., 2020; Energy Resources of Australia, n.d.). This would seem to suggest that the Commonwealth government, while recognizing the promise of LiDAR applications, is still working with operators to establish reliability of the technology with regards to reclamation monitoring and in relation to ground-based data collection, and maintaining strict reporting oversight when it comes to proposals using remote sensing technologies.

State Governments

Many of the states have recently updated their mine reclamation and reporting guidelines (2017-2021). Nearly all of these updates have included an emphasis on the benefits of using remote sensing technology in reclamation. New South Wales (NSW) is the most recent, as the NSW Resources Regulator is currently in the process of consultation on its updated guidelines, ending on April 30th, 2021 (Utz, 2021; McCredie et al., 2020; New South Wales Department of Planning, Industry and Environment, 2020). The third of the state's six new guidelines for review covers reclamation controls and promotes the use of UAVs and multispectral or LiDAR data for additional inspections and analysis of vegetation establishment (including germination and plant health), weed infestation and soil stability (including erosion and drainage). Monitoring of these factors must continue until vegetation is well established and the site is considered stable; findings are compared against objectives and completion criteria (New South Wales Resources Regulator, 2021).

South Australia updated mining regulations in 2020 and provides a variety of guidance documents to assist lease holders in their regulatory reporting (South Australia Department for Energy and Mining, 2021). The guidance document for mining compliance reports indicates that UAV imagery can be used (in a similar capacity to, or in conjunction with land-based surveys and/or satellite imagery) to establish compliance with environmental objectives for mining leases (South Australia Department for Energy and Mining, 2020).

A new guidance document on mine closure and reclamation was released in Western Australia in 2019, partially funded and endorsed by the state government, with other partners including research institutions and industry operators. This document is intended to complement existing legislation and highlights remote sensing for use in monitoring vegetation establishment. Remote sensing technologies, including LiDAR, photogrammetry, and platforms such as UAVs and satellites, are especially promoted in high-risk areas, such as those at risk from disturbance through traditional ground-based monitoring (Young et al., 2019).

In Tasmania, reporting guidelines for mining and exploration lease holders was updated in 2017. These reports cover current operations and reclamation progress, and required data includes remote sensing and/or LiDAR data, which must be presented in raw and processed versions (Tasmania Department of State Growth, 2020). Particulars of the remote sensing data type or purpose are not specified.

Similar to the Orphan Wells program in Alberta, state and territory governments have taken responsibility for the reclamation of certain legacy or abandoned mines under their jurisdictions. In this capacity, the Northern Territory government uses UAVs to conduct a first assessment of reclaimed areas, and will only assess on foot if any anomalies or areas requiring further inspection are found; this has increased safety and reduced site inspection time (Northern Territory Department of Industry, Tourism and Trade, 2021).

8.2.2 Environmental Monitoring and Forestry

Major environmental concerns in Australia included distribution of water resources, and the cessation of illegal land clearing. As a result, important innovations in remote sensing are also being applied in these areas. The forestry sector, as in many Canadian jurisdictions, is also pioneering remote sensing techniques. Many of the applications in these sectors can be similarly employed in mine reclamation monitoring, and a few interesting cases are highlighted below.

Water

The Murray-Darling Basin is the drainage basin for several major rivers in Australia, and home to one of the country's most significant agricultural areas. This area also spans several states, so the Commonwealth government created the Murray-Darling Basin Authority (MDBA) in 2018 to monitor and regulate water use and related environmental impacts in this basin, with a combination of rapid satellite re-imaging (entire area every five days) and gauge flow data. With this data, the MDBA monitors water flow through the area, which helps to monitor and understand changes in the landscape (e.g. water storage, vegetation) over time. This in turn helps to determine compliance with the strategic plan for the basin and evaluate the effectiveness of the basin plan for equitable water resource distribution and environmental protection (Murray-Darling Basin Authority, 2020). This is an interesting application of remote sensing to both compliance enforcement and policy adaptability.

Illegal Land Clearing

Both Queensland and South Australia use remote sensing to detect and enforce legislation against illegal land clearing (Hamman, 2019; SA Dept Envt & Water, 2013&2015). Remote sensing data is subject to manual validation when changes in vegetation cover are detected through an automatic analysis, which verifies the change in vegetation. Once illegal land clearing is confirmed, fines and/or criminal proceedings may result (South Australia Department for Environment and Water, 2020), and the remote sensing data may be applied in court proceedings (Hamman, 2019). The detection of vegetation cover changes is also an important part of reclamation monitoring, and it may be valuable to know that there is legal standing to apply this data in court proceedings in other jurisdictions.

Forestry

The NSW Department of Primary Industries' Forest Management Framework promotes the use of LiDAR for various forestry applications. This includes identifying potential areas of erosion, delineation of drainage and riparian areas, and developing predictive tree models that can identify areas with higher growth potential from canopy height (New South Wales Department of Primary Industries, 2018). This again highlights the value of remote sensing technologies in identifying areas of erosion, while also demonstrating their usefulness for distinguishing different vegetation communities, drainage patterns, and growth potential of sites, all of which could be applied to reclamation monitoring.

8.2.3 Summary

In Australia there is an emphasis on government regulators providing clear guidance documents to industry operators, outlining their expectations as well as recommended strategies for reporting and operations. In terms of technology use, LiDAR, UAV aerial photographs and satellite imagery, used individually or in combination, with various levels of data processing, were all promoted in multiple states and by the Commonwealth government. Applications largely target vegetation and soil erosion monitoring in mine reclamation and also related fields like forestry and land clearing. Remote sensing techniques are not the only monitoring method used in these instances, but are complemented by, or used to augment, traditionally collected field data. At this time, ground truthing of remote sensing data is still required for validation, as many of the jurisdictions and guidance documents have only recently (since 2018) started to promote these technologies in earnest.

8.3 The United States of America

While each state enjoys a good measure of independence in terms of governance, the federal government still operates many departments and bureaus with nation-wide jurisdiction, greater consistency in approaches, and with state or region-specific branches. This portion of the review will primarily focus on federal approaches and ongoing development of remote sensing technologies as a result.

8.3.1 Reclamation

The Office of Surface Mining Reclamation and Enforcement (OSMRE), under the federal Department of the Interior (DOI), oversees and enforces the *Surface Mining Control and Reclamation Act* of 1977 (SMCRA). In this capacity, OSMRE uses satellite imagery and UAV data collection to support SMCRA programs, and their Technical Innovation and Professional Services (TIPS) team keeps abreast of latest developments in remote sensing technology for future applications (Office of Surface Mining Reclamation and Enforcement, 2020).

OSMRE has conducted various trials of remote sensing technology, namely UAVs, in its role overseeing the SMCRA. Such trials have included using:

- Stereo images taken with UAVs to monitor revegetation and map stream channels at a former coal mine in New Mexico (U.S. Department of the Interior, 2013a)

- Satellite imagery to inspect, evaluate, and identify potential regulatory issues prior to field visits for active coal mine inspections, increasing accuracy of inspections while decreasing time spent (U.S. Department of the Interior, 2013b)
- Stereo images taken with UAVs to inspect mine sites in remote areas that are difficult to access safely in Colorado, and produce an accurate classification of on-site vegetation for regulatory purposes (U.S. Department of the Interior, 2012a)
- A Digital Surface Model (DSM) generated from stereo satellite imagery in litigation over land contours with a coal company in Oklahoma (U.S. Department of the Interior, 2012b)
- Ground-based LiDAR to generate detailed elevation data, identify vegetation types, and calculate biomass at reclaimed and yet-to-be reclaimed sites at a coal mine in Arizona (U.S. Department of the Interior, 2017)
- A combination of LiDAR, satellite imagery, and historical aerial imagery to monitor and assess in-progress reclamation of a mine in Utah (U.S. Department of the Interior, 2018a)
- UAV stereo images to create 2D and 3D models of active and abandoned coal mines, which are in turn used for products like pit volume calculations to determine amount of backfill material required (U.S. Department of the Interior, 2018b)

While such trials are an important step for validating remote sensing technologies and demonstrating their applications, OSMRE has not yet formalized regulatory requirements for remote sensing technology in reclamation monitoring by operators (see Section 4.1).

Regardless, increased used of remote sensing technologies for reclamation monitoring requires establishment of standardized survey methods. Michael Curran, a PhD student at the University of Wyoming, has developed a standardized system via UAV to compare reclamation sites against their undisturbed reference sites in a more objective way than traditional ground-based survey methods. With the UAV, assessors can use randomly selected points to navigate the UAV to, and use the UAV to collect imagery for later assessment. This also reduces the need to have vegetation identification conducted in the field, as it can be completed later with the collected imagery. This also creates a permanent record of the survey that can be re-referenced and re-analyzed at later dates if need be. Using this method and UAVs allows for much more rapid assessment of larger areas than is possible with ground-based surveys (McKim, 2020).

Similarly, in Utah the state government is collaborating with Utah State University to develop a landscape monitoring tool to aid operators in reclamation activities in the state. In this project, UAV imagery and topographic data are being used to find microsites for vegetation establishment. The goal has been to focus on methods that will be broadly applicable and work as a template for other, similar sites in the state to increase vegetation establishment success and monitor reclamation success (Harris, 2021).

8.3.2 Other Industries

Many Departments, Bureaus, and other agencies are using, recommending, and or trialing remote sensing, often as part of best management practices (BMPs), for various types of environmental monitoring (U.S. Department of the Interior Bureau of Land Management & U.S. Department of Agriculture Forest Service, 2007; Utah Department of Environmental Quality, 2020; U.S. Department of Agriculture Forest Service , n.d.; U.S. Department of the Interior National Park Service, 2017). For instance, remote well monitoring in the oil and gas industry is recommended as a BMP both federally and at the state level as a strategy to cut down on noise and air pollution, particularly in sensitive areas (U.S.

Department of the Interior Bureau of Land Management & U.S. Department of Agriculture Forest Service, 2007; Utah Department of Environmental Quality, 2020).

Many agencies also use remote sensing, particularly aerial photographs from UAVs, to aid in land management and vegetation monitoring, as well as enforcement of regulations and detection of illegal activities (U.S. Department of Agriculture Forest Service, n.d.; U.S. Department of the Interior Bureau of Land Management, n.d. a; U.S. Department of the Interior National Park Service, 2017). The Bureau of Land Management (BLM) under the DOI has developed a standardized monitoring strategy for their public lands (AIM – Assessment, Inventory, and Monitoring Strategy), which involves remote sensing in support of vegetation monitoring as a key approach (U.S. Department of the Interior Bureau of Land Management, n.d. a; U.S. Department of the Interior Bureau of Land Management, n.d. b). The US Department of Agriculture (USDA) Forest Service also indicates UAVs' potential with regards to estimating biomass, establishing the effectiveness of vegetation treatments, and determining the success of revegetation management objectives.

8.3.3 Summary

While a good deal of research and remote sensing data collection occurs in the US, in general, US government agencies are not overly forthcoming with the specifics of their approaches. It is also likely that due to UAV regulatory issues through the Federal Aviation Administration, progress with application of at least this platform is slow. However, there are still many applications in vegetation monitoring, both for reclamation and for related fields, and ongoing research into improving and standardizing methods.

9.0 CONCLUSION

As seen through jurisdictions in Canada, Australia, and the US, remote sensing technologies show a good deal of promise in regulatory application, both in mine reclamation and monitoring, and in related fields with similar needs for environmental monitoring and assessment such as aggregate mining and oil and gas development.

There are two main caveats with the application of these relatively recent technologies. The first is that these are never 100% automated approaches to reclamation planning and monitoring. An investment of time and personnel are still required to process and interpret any data obtained from remote sensing. For instance, the Queensland team that investigates illegal land clearing employs roughly 12 people to monitor the data created, check for errors, create an annual report on land use change, and prepare evidence of potential violation (Hamman, 2019); for reference this state has a population of just over 5 million and a land area of 1.7 million km^2, while Alberta's current population is slightly smaller and its land area is about one third of Queensland's.

Second, applications of remote sensing technologies will need to be tested and verified before broader application can be successful. Tests should consider establishing standardized and easily reproducible methods that are simple enough for a wide variety of stakeholders to employ, while still generating accurate and useful data. The best methods will perhaps even improve upon certain aspects of traditional ground-based data collection, such as the potential for subjectivity in sampling location (see for example McKim, 2020).

When applied correctly, remote sensing technology can save time in field assessments, increase frequency of inspections, minimize the need to access remote or unsafe areas, and create highly detailed raw data that can be used to develop a variety of products with direct application to reclamation processes.

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