RAPID ASSESSMENT OF LEGACY PIT RESTORATION SUCCESS:

A Pilot Project Report to TOARC

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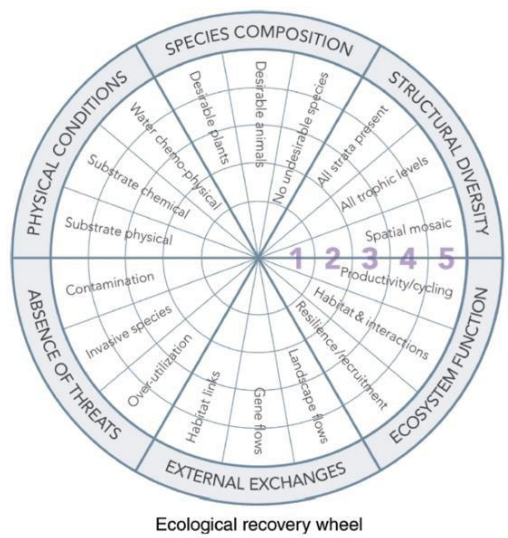
December 20, 2023

1 Introduction:

The rehabilitation of pits and quarries is an important step in the sustainable management of former aggregate resource extraction sites in Ontario, Canada. Rehabilitation of these sites helps to transition the land from aggregate extraction to other productive land use activities, with the goal of addressing social, economic, and environmental concerns. The Ontario Aggregate Resources Corporation (TOARC), through the Management of Abandoned Aggregate Properties (MAAP) program, is responsible for the rehabilitation of former pits and quarries, ensuring the land is restored to a naturalized state. This often involves grading the site to smooth waste material, spreading soil to cover depressions, and hydroseeding native plant species to start the growth of vegetation. Additional research is required to determine the state of naturalization of former pits and quarries in Ontario. Nearly 600 legacy rehabilitation projects, with over 300 in the natural environments, have been completed through the MAAP program, and over 8,400 sites have been rehabilitated by licensees and permittees in Ontario.

Restoration science has advanced considerably from a simple presence/absence species inventory of a site. The ecological recovery of a restored site is assessed on 18 different metrics from six separate attributes: site physical conditions, species composition, site structural diversity, ecosystem function, and the absence of threats (Gann et al., 2019). Quantifying these metrics traditionally involves significant field and lab analysis over several sampling periods. Even simple plant species composition of a site needs to be done at least three times over the growing season to account for different growth habits of disparate vegetation guilds. While soil structure (bulk density, organic matter content, porosity) doesn't change much on a seasonal scale, spatial variability in these metrics requires significant field work. Nutrient cycling and measures of ecosystem production and respiration, as well as soil water content, should be measured throughout a growing season.



Gann et al., (2019) Restoration Ecology, 27 (S1): S1-S46

Remotely sensed drone images have become popular for measuring vegetation status (De Castro et al., 2021; Fawcett et al., 2020) and monitoring post-disturbance recovery in various fields, including grasslands (Neumann et al., 2021), forestry (Qi et al., 2022), and agriculture (Hafeez et al., 2023). Thus, there is potential to use various image analysis techniques to significantly reduce the field and lab efforts needed to assess quarry and pit rehabilitation success without significantly compromising confidence in the assessment. There is limited information on the ecological status of the nearly 300 remediated projects. Demonstrating to the public a level of success in restoration would benefit TOARC and the natural resource industry. Similarly, if sites are not met with success, gathering information on why that is will inform future planning activities.

Problem: Full field assessment of all completed MAAP projects would be time consuming and costly; thus, a consistent, quick and/or remote sensing method that captures the dynamics of assessment of restoration success is needed to inventory the bulk of these remediated sites.

Goals: The overall goal of this PILOT project is to collect a range of data and develop field, lab, and remote sensing methods to evaluate the level of success of previously rehabilitated sand and gravel pits. Specifically, using three test legacy sites and nearby reference sites, we seek to: (1) determine the key ecosystem functions that most directly contribute to successful restoration in aggregate pits; (2) examine which of these functions can reliably be estimated through remotely sensed image analysis; and (3) develop methods of evaluation, such that a defensible protocol can readily be applied to many more aggregate pit restoration projects.

2 Methodology:

2.1 Selected Sites Visited in the Summer of 2023:

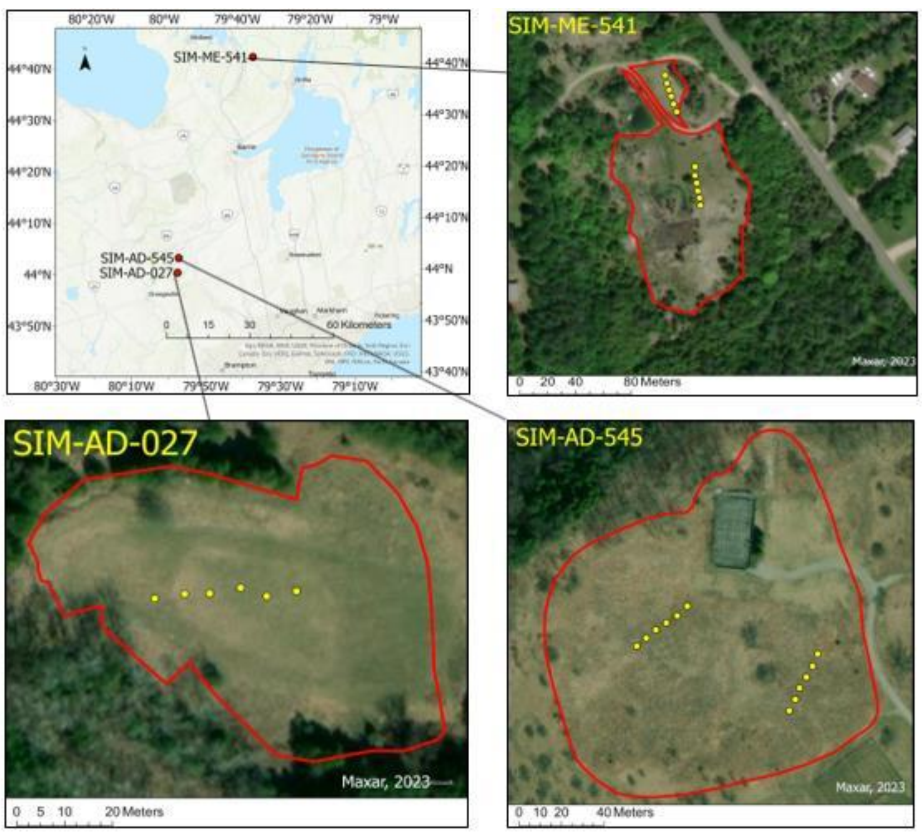


Figure 1: The three site locations, the transects and the plots (yellow dots) along the transects in each site.

The pilot project was carried out during the summer of 2023 and investigated the status of vegetation and soil in three sites in southern Ontario rehabilitated by TOARC. The three sites include SIM-AD-545 in Orangeville, SIM-AD-027 in Orangeville, and SIM-ME-541 in Coldwater (Figure 1). The species seeded at each site during the rehabilitation process can be found in Table 1.

Table 1: Species seeded at each site during rehabilitation work.

Study Site	Rehabilitation Year	Species Seeded
SIM-AD-027	2017	Black-Eyed Susan (Rudbeckia hirta), Canada Wild Rye (Elymus Canadensis), Indiangrass (Sorghastrum nutans), Little Bluestem (Schizachyrium scoparium), New England Aster (Aster novae-angliae), Wild Bergamont (Monarda fistulosa), Canada Goldenrod (Solidago Canadensis), Common milkweed (Asclepias syriaca), Sand Dropseed (Sporobulus cryptandrus), and Smooth Blue Aster (Aster laevis)
SIM-AD-545	2006	Big bluestem (Andropogon gerardii), Butterfly milkweed (Asclepias tuberosa), Heath aster (Aster ericoides), Sky Blue aster (Aster ooentangiensis), New England aster (Aster novae-angliae, Tall Coreopsis (Coreopsis tripteris), Showy tick-trefoil (Desmodium canadense), Canada wild rye (Elymus canadensis), Marsh sneezeweed (Helanthum autumnal), Oxeye (Heliopsis helianthoides), Roundhead bushclover (Lespedeza capitata), Dense blazing star (Liatris spicata), Wild bergamont (Monarda fistulosa), Evening primrose (Oenothera biennis), Switch grass (Panicum virigatum), Virgina mountain mint (Pycnanthemum Virginianum), Gray Coneflower (Ritibida pinnata), Black-Eyed Susan (Rudbeckia hirta), Little blue stem (Schizachyrium scoparium), Grey Goldenrod (Solidago nemoralis), Stiff goldenrod (solidago rigida), Indian grass (Sorghastrum nutans), and Sand drop seed (Sporobulus cryptandrus)
SIM-ME-541	2019	Red Top (Agrostis gigantea), Canada Bluegrass (Poa compressa), Creeping Red Fescue (Festuca rubra), Birdsfoot Trefoil (Lotus corniculatus), Alsike Clover (Trifolium Hybridium), White Clover (Trifolium repens), Perennial Rye Grass (Lolium perenne), and Meadow Fescue (Festuca pratensis)

SIM-AD-027:
Located 6 km southward of SIM-AD-545. SIM-AD-027 underwent rehabilitation in 2017. The terrain is characterized by uneven topography, surrounded by forests, offering valuable insights into the site's historical condition. This site contains varying ground cover, with limited sections of bare soil and most of the site flourishing with vegetation.

SIM-AD-545:
This site is located at a winery perched atop a hill in Orangeville. SIM-AD-545 was rehabilitated by TOARC in 2006. It is south of forested land, with agricultural and residential use on the surrounding sides. The terrain is undulating, with steep hills and diverse vegetation, including areas that have naturally reforested since the site was rehabilitated and large sections of bare soil or dead grass.

SIM-ME-541:
Located in Coldwater, Ontario. SIM-ME-541 stands out as the most recently rehabilitated site in 2019. The terrain is flat, except for a mound of unsorted debris to the northeast and two ponds to the west. The land surrounding the ponds is dry and covered with moss and low grasses. SIM-ME-541 is encircled by forests with a large gravel driveway running through the center of the site.

2.2 Data Collection

A range of field data, including drone images, vegetation composition, and soil samples were collected from May to September 2023 in all three sites on the schedule found in Table 2. Field data and plant samples were collected in six plots with 6-meter spacing along two transects in SIM-ME-541 and SIM-AD-545 and one transect in SIM-AD-027. We placed a 50 cm by 50 cm metal quadrat in each plot to measure species composition and collect field samples.

Table 2: Field visits and field data collected at each site.

Sites	Drone imaging	Species Composition	Soil Moisture	Quadrat Photos	Soil Samples
SIM-AD-027 (1 transect)	May 19 July 5 August 2 August 28	July 10 August 1 August 24	July 5 August 1 August 24	July 10 August 1 August 24	September 25
SIM-AD-545 (2 transects)	May 19 July 5 July 30 August 28	July 5 July 10 August 24	July 5 July 30 August 24	July 10 July 30 August 24	September 25
SIM-ME-541 (2 transects)	July 7 August 2 August 27	July 7 August 2 August 31	July 7 August 2 August 31	July 10 August 2	September 26

Drone Imagery:

A DJI Mavic 3 Enterprise Thermal drone was flown across each site from May to August with two imaging sensors, a red, green, and blue (RGB) sensor at 20 MP, and a thermal band sensor at 0.3 MP. In August, a DJI Mavic 3 Multispectral Edition was used with five imaging sensors, an RGB sensor at 20 MP and four image sensors capturing green, red, red-edge, and near-infrared at 5 MP each.

Species Composition:

A catalogue with the species name, percentage of species presence in each quadrat, and percentage of green coverage of each quadrat along the transect was recorded on each visit. Plant samples were identified by a biology expert, an app called Seek, and from quadrat images.

Soil Moisture and Soil Samples:

A HydroSense 620 Water Content Sensor was used to take three measurements in each quadrat in each field visit for vegetation sampling. Additionally, soil moisture content was measured throughout the three sites in late September to assess the spatial variability within each site.

During the late-September visit, surface soil samples were collected from each vegetation quadrat at each site using constant-volume tins determination of bulk density. Additionally, across all three sites, soil samples were taken from the upper 0-10 cm, and where possible, 10-20 cm for subsequent lab analysis. Subsamples of the air-dried soil were analyzed for organic matter content using the loss-on-ignition method (550 °C for 4 hours), soil pH (20 g soil, 40 mL Milli-Q deionized water), and heavy metal concentration using a cold nitric acid digestion procedure (Groenenberg et al., 2017).

Quadrat Photos:
High-resolution photos of each quadrat were taken using an iPhone 12, iPad Air and Nikon D7500 cameras. These photos support species identification further in the lab setting, as a complement source to the field data.

2.3 Image Processing and Analysis

Image Pre-Processing:
Drone images were imported into the Pix4Dmapper software where each image was processed in three stages: 1) initial processing 2) point cloud creation and 3) Orthomosaic and index calculation. Initial processing involves aligning the thousands of individual images into a seamless mosaic by locating matching points between each image. Discrepancies in the alignment between each image caused by GPS inaccuracies and camera lens distortions are calibrated during this stage. Next, the 3-dimensional location of every object seen within the mosaic is extracted to create a dense grid of points, called a point cloud. Finally, an Orthomosaic was produced where the distortions caused by drone perspective and image color were corrected to produce a seamless image. During this stage, any images captured by the DJI Mavic 3 Multispectral drone were radiometrically corrected for sun irradiance and sun angle using measurements from the drone's downwelling light sensor.

Image Classification for Species-Level Mapping:
A convolutional neural network was trained to quantify the vegetation present for each site after each visit. Training for each neural network took place in the ArcGIS Pro software using thousands of classified image tiles where each tile contained an object present within the site (i.e. grass, dirt, rocks). The neural network learned to distinguish these objects by analyzing thousands of image tiles, and the learning process was governed by a series of parameters. Once the model was trained it was used to classify drone images. In the future, the neural network can be optimized, trained to recognize new objects, and then used to classify images without being trained (a process known as inferencing).

Regression Modelling for Fractional Covers:
We selected thirty sampling points in each site with varying levels of coverage, ranging from little to no vegetation to full green vegetation coverage. At each sampling location, the factional cover percentages were estimated according to the following categories from a square consisting of 8 × 8 cells, with each cell sized at 40 cm × 40 cm: grass fractional cover percentage, soil fractional cover percentage, tree/shrub fractional cover percentage, and dead material fractional cover percentage. Median spectral information in the red, green, blue and near-infrared (late August only) bands were calculated for each square. A spectral index is calculated from the median spectral data as an independent variable and used in conjunction with the fractional cover estimates from 30 squares as the dependent variable to create linear regression models for predicting fractional cover for each site.

3. Results
3.1 What Field Data Tells Us

SIM-AD-027:

During early July and late August, this site (Table 3) exhibited a diverse array of 13 species, with 54% classified as invasive and the remaining 46% as native. Dominant native species included grass, Common Goldenrod, and Pubescent Sedge, while Cow Vetch, Birdsfoot Trefoil, and Smooth Brome emerged as the most abundant invasive species. Notably, Cow Vetch dominated in early July and ranked second in late August. Grass, on the other hand, claimed the top spot for abundance in both months and experienced significant growth over this period. Originating from the initial seed mix applied during rehabilitation, grass played a pivotal role in the site's vegetation. Invasive species, except for Cow Vetch, Birdsfoot Trefoil, Smooth Brome, and Bedstraws, generally constituted less than 5% of the vegetation. Peak vegetative growth occurred in early July and August across most species in site SIM-AD-027.

Table 3: Species Composition and Abundance (%) in Site SIM-AD-027 in July and August.

Species Common Name	July 10	August 1	August 24	In Seed Mix?
Cow Vetch*	29	14.3	17.8	No
Grass	6.7	24.2	27.5	Yes
Common Goldenrod	2.5	16.7	16	No
Birdsfoot Trefoil*	0	2.7	10.8	Yes
Smooth Brome*	12	0.8	0	No
Pubescent Sedge	12.7	0	0	No
Bedstraws*	7.5	4.5	0	No
Queen Anne's Lace*	0	2.5	1.5	No
Common Horsetail*	0	2	0	No
Violets*	1.2	0.5	0	No
Switchgrass	1.2	0	0	No
American Asters	0	0.8	0	No
True Sedges	0.7	0	0	No

Note: * indicates invasive species.

In September 2023 the soils of site SIM-AD-027 were dry, with soil moisture averaging 17 %. Additionally, across the site, soil moisture content ranged by a factor of four, from 8 % to 28 % (Fig. 2). This low moisture likely limits species diversity and productivity. The high variability in soil moisture likely impacts the distribution of some plant species. Soil pH averaged 7.75 at the surface, increasing to 8.27 at 90-cm depth. There is no concern with these levels. Soil organic matter was low, with only a maximum of 6.5 % in the surface soils (0-5 cm), and lower depths all less than 4%. These low levels of soil organic matter likely limit ecosystem processes. All samples of soil from the SIM-AD-027 site were found to contain levels of heavy metals below the Canadian critical limits of toxicity in sediment (Table 4). It is therefore evident that the rehabilitation of this site did not negatively impact the soil contamination load, and it is unlikely that these metals would negatively impact the vegetation community.

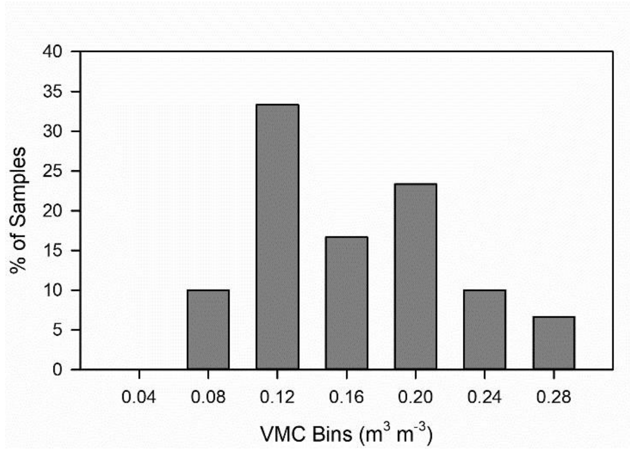


Figure 2: Frequency histogram of surface (0-8 cm) soil moisture measurements across the SIM-AD-027 site in late September.

Table 4: Mean bioavailable metal concentration (mg kg^{-1}) in soils of the three sites and Canadian critical load thresholds.

Element	Threshold	AD-027	AD- 545	ME-541
Cadmium	2.0	<0.1	<0.1	<0.1
Chromium	3.0	<0.1	1.6	<0.1
Cobalt	3.0	1.8	2.2	1.1
Copper	60	33.2	41.3	29.1
Lead	12	8.4	7.1	5.5
Lithium	55	22.4	51.4	48.4
Nickel	42	17.2	22.9	11.4
Zinc	225	174.6	163.3	215.8

SIM-AD-545:

This site (Table 5) featured nine species across transects from early July to late August, with invasive species accounting for 44% and native species for approximately 54% of the site's abundance. Pubescent Sedge, Switchgrass, and grass were the prominent native species, while Smooth Brome and Bladder Campion dominated as invasive species. Pubescent Sedge maintained consistent abundance throughout visits, whereas Switchgrass and other grasses exhibited an increase in late July, followed by a decrease in late August. Both were part of the original seed mix, alongside a species akin to Pubescent Sedge. Pubescent Sedge and Switchgrass claimed dominance in early July and late July, respectively. However, invasive species, including Smooth Brome and Bladder Campion, remained below the 5% threshold. The most vigorous vegetative growth was observed in early July and late August for both native and invasive species.

Table 5: Species Composition and Abundance (%) in Site SIM-AD-545 in July and August.

Species Common Name	July 10	July 30	August 24	In Seed Mix?
Pubescent Sedge	22.25	21.55	23.6	Maybe
Switchgrass	19.35	22.3	15.5	Yes
Grass	8.15	13.15	9.4	Yes
Moss	3	0	3.25	No
Smooth Brome*	1.75	0	1.5	Maybe
Bladder Campion*	1.35	0	1.5	No
Balsam Poplar	0.65	0	1.25	No
Common Salsify*	0.4	0.65	0.4	No
Purple Loosestrife*	0.1	0	1.15	Yes

Note: * indicates invasive species.

In September 2023 the soils of site SIM-AD-545 were dry, with soil moisture averaging 15 %. Additionally, across the site, soil moisture content ranged by a factor of four, from 8 % to 28 % (Fig. 3). This low moisture likely limits species diversity and productivity. The high variability in soil moisture likely impacts the distribution of some plant species. Soil pH averaged 8.03 at the surface, increasing to 8.52 at 90-cm depth. There is little concern with these levels, though the deeper soil is trending toward too alkaline. It is noted, however, that many locations at this site did not have > 50 cm of soil development. Soil organic matter was low, with only a maximum of 5.9 % in the surface soils (0-5 cm), and lower depths ranging from < 2 % to a maximum of 4.5 %. These low levels of soil organic matter likely limit ecosystem processes. All samples of soil from the SIM- AD-545 site were found to contain levels of heavy metals below the Canadian critical limits of toxicity in sediment (Table 4). It is therefore evident that the rehabilitation of this site did not negatively impact the soil contamination load, and it is unlikely that these metals would negatively impact the vegetation community.

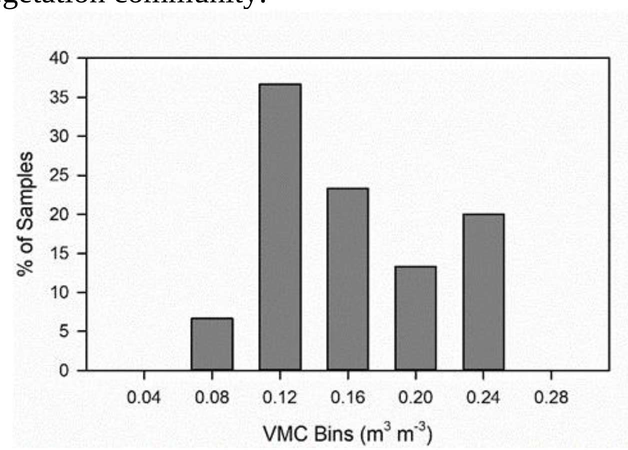


Figure 3: Frequency histogram of surface (0-8 cm) soil moisture measurements across the SIM-AD-545 site in late September.

SIM-ME-541:

In SIM-ME-541 (Table 6), 21 species were identified, with 61% classified as invasive and 39% as native. True Sedges and Red Fescue emerged as the most abundant native species, while Common Ragweed, Salad Burnet, and Sickle Alfalfa dominated as invasive species throughout July and August. Moss is quite abundant throughout the site, too. True Sedges displayed a significant increase in presence from early July to August, whereas moss and Red Fescue witnessed a decrease. Red Fescue was the primary species in early July, disappearing by late August, while True Sedges claimed the top spot in both months. The original seed mix applied during rehabilitation included species resembling True Sedges and Red Fescue. Most invasive species maintained a low abundance, consistently below 5% throughout the growing season. Peak vegetative growth was observed in early July and August for both native and invasive species.

Table 6: Species Composition and Abundance (%) in Site SIM-ME-541 in July and August.

Species Common Name	**July 10**	**August 2**	**August 31**	**In Seed Mix?**
True Sedges	3.4	12.4	19.3	Maybe
Moss	13.2	7.45	6.85	No
Red Fescue	23.95	5.75	0	Maybe
Common Ragweed*	0.9	2.25	6.75	No
Grass	0.9	4.9	4.9	Yes
Small’s Ragwort	0	4.15	6.25	Maybe
Salad Burnet*	1.6	1.95	2.85	No
Sickle Alfalfa*	0	2.35	3.25	No
Common Bird's-Foot Trefoil*	5.25	0	0	Yes, non-invasive version
Hawkweeds*	0	2.4	2.5	No
Evening Primrose	0	0.25	3.75	No
Ribwort Plantain*	3.8	0	0	No
Hawkweed*	0.4	0	2.5	No
Viper's Bugloss*	0.65	0.25	0.75	No
Common Goldenrod	1.15	0	0	No
Cow Vetch*	0.85	0	0	No
Sweet Clovers*	0	0.25	0.6	No
Variegated Scouring Rush	0.35	0	0	No
White Sweetclover*	0.15	0	0	No
Common Yarrow*	0.15	0	0	No
Tall Goldenrod*	0.1	0	0	No

Note: * indicates invasive species.

In September 2023, the soils of site SIM-ME-541 were very dry, with soil moisture averaging 12 %. Additionally, across the site, soil moisture content ranged by a factor of five, from 4 % to 20 % (Fig. 4). This low moisture likely limits species diversity and productivity. The high variability in soil moisture likely impacts the distribution of some plant species. Soil pH averaged 7.82 at the surface; however, some surface soils were quite alkaline, with maximum values of 8.68, which is considered alkaline enough to limit plant health through restricting access to key macro- and micro-nutrients. The soils at site SIM-ME-541 were shallow, with depth to refusal occurring at 20 cm in the deepest locations; most sample locations were less than 10 cm deep. This shallow soil likely limits plant development. Soil organic matter was very low, with an average of < 3 % in surface soils (0-5 cm), and < 2 % in the deeper soil samples (5-10 cm). These low levels of soil organic matter likely limit ecosystem processes. All samples of soil from the SIM-AD-545 site were found to contain levels of heavy metals below the Canadian critical limits of toxicity in sediment (Table 4). It is therefore evident that the rehabilitation of this site did not negatively impact the soil contamination load, and it is unlikely that these metals would negatively impact the vegetation community.

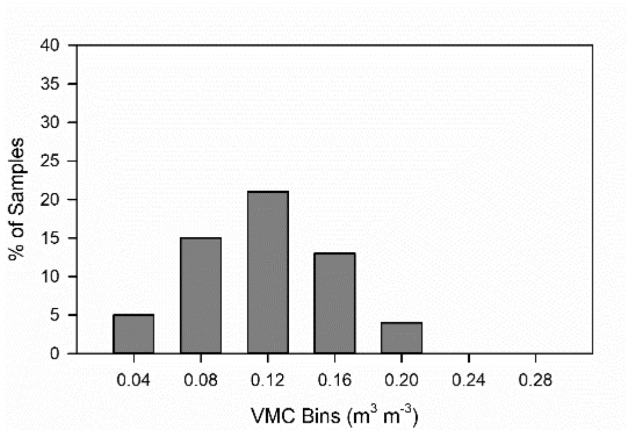


Figure 4: Frequency histogram of surface (0-8 cm) soil moisture measurements across the SIM-ME-541 site in late September.

3.2 Percentage Cover Maps

True color imagery (RGB) was created in Pix4Dmapper through image mosaicking and can be found below in Figures 5, 8, and 11. From the true color images, data from 30 sampling points in each site were obtained to build a robust linear regression model for each site, using spectral indices as independent variables and the observed percentage cover data as dependent variables. The best regression model for each site and each fractional cover type (i.e., green, and dead) was then used to create the percentage green vegetation cover maps and percentage dead material cover maps.

SIM-AD-027:

Percentage green cover maps demonstrated variation in the spatial distribution and temporal change of the site. Site SIM-AD-027 (Figures 5 and 6) exhibited clustered green cover on its western side, observed in Figure 6. As the growing season progressed, the green cover began to increase to the east side while becoming denser around what had already grown, and then very dense in early August. Towards the end of August, the greenness decreased as plants died off.

The percentage of dead cover maps demonstrated areas within the site comprised of dead vegetation. Site SIM-AD-027 (Figure 7) began as primarily dead vegetation clustered to the east half and became much more dispersed and smaller in size as the season progressed into July and late August.

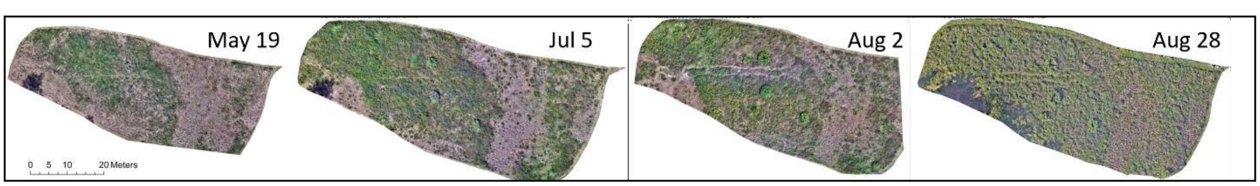


Figure 5: SIM-AD-027 True Color (RGB) Imagery in May, Early July, Late July, and Late August

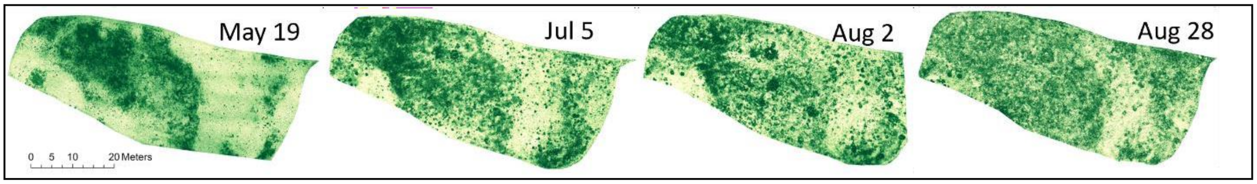


Figure 6: SIM-AD-027 Percentage Green Cover Maps from May, Early July, Late July, and Late August

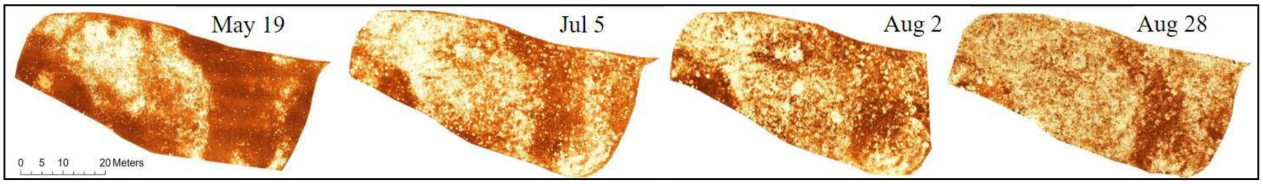


Figure 7: SIM-AD-027 Percentage Dead Cover Maps from May, July, Early August, and Late August

SIM-AD-545:

Site SIM-AD-545 (Figures 8 and 9) had extremely sparse green cover in early May, with some clustering near the North section. On July 5th, denser vegetation began to grow around the southern and outer edges of the site. On July 30th, the elevation variation in the site became apparent through the dense vegetation having grown to the eastern side and lighter, less green cover on the western side. This site became the greenest in late August, with an overall high green cover distributed across the site.

In terms of dead material fractional cover, SIM-AD-545 (Figure 10) exhibited much more variation, initially being heavily dead vegetation in May, shrinking into early July, and then becoming primarily concentrated on the eastern side of the site in late July, before diminishing in late August as green cover increased significantly.

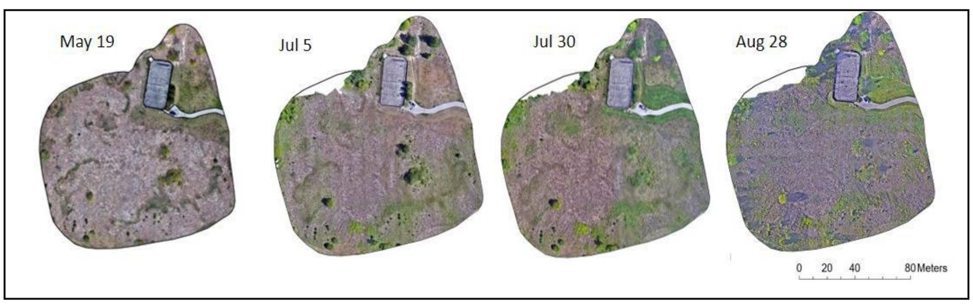


Figure 8: SIM-AD-545 True Color (RGB) Imagery in May, Early July, Late July, and Late August

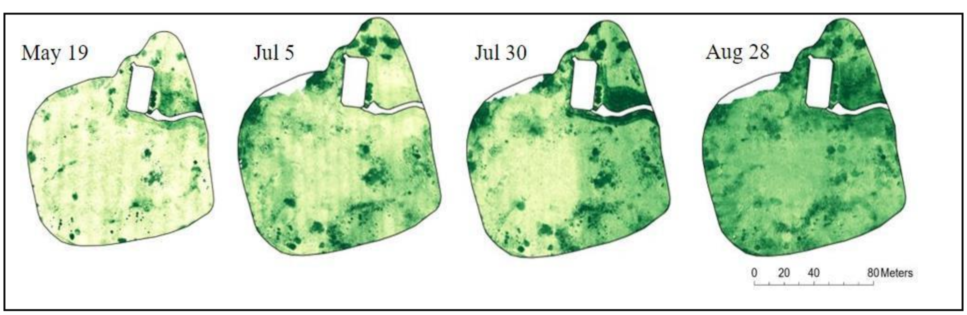


Figure 9: SIM-AD-545 Percentage Green Cover Maps from May, Early July, Late July, and Late August

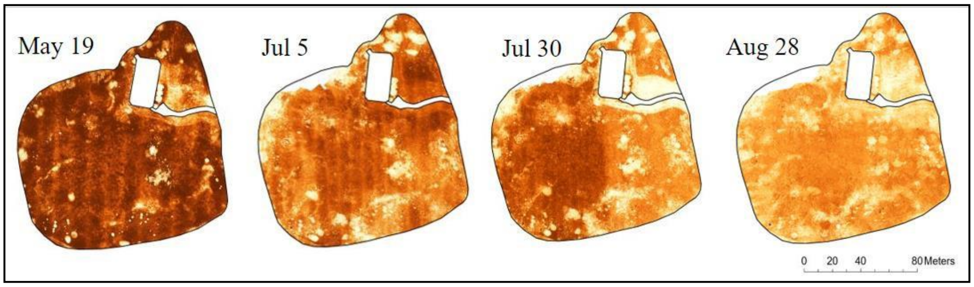


Figure 10: SIM-AD-545 Percentage Dead Cover Maps from May, Early July, Late July, and Late August

SIM-ME-541:
The third site, SIM-ME-541 (Figures 11 and 12) contained overall a higher amount of dead cover except for trees and sparse green vegetation cover. The low soil moisture content and quality resulted in higher amounts of dead cover being preserved over the growing season with less green cover to replace it.

In terms of dead material fractional cover, SIM-AD-545 (Figure 10) exhibited much more variation, initially being heavily dead vegetation in May, shrinking into early July, and then becoming primarily concentrated on the western side of the site in late July, before diminishing in late August as green cover increased significantly.

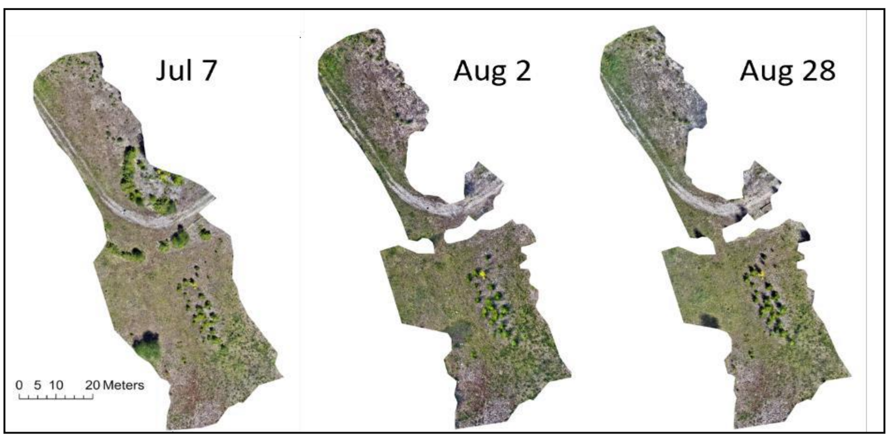


Figure 11: SIM-ME-541 True Color (RGB) Imagery from July, Early August, and Late August

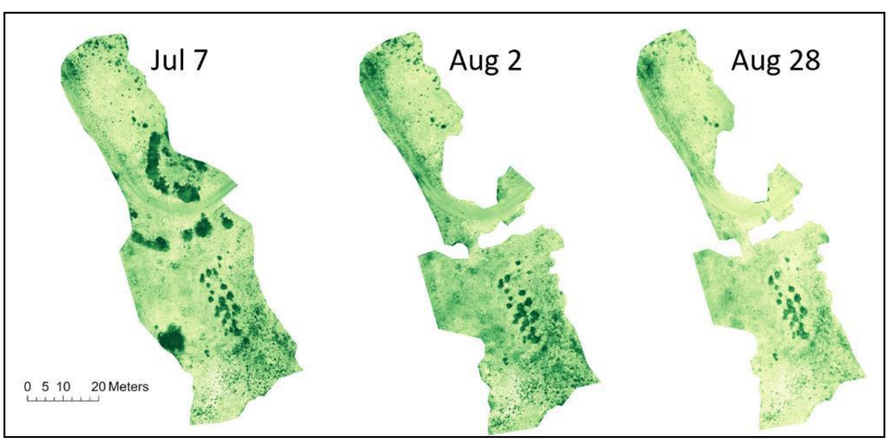


Figure 12: SIM-ME-541 Percentage Green Cover Maps from Early July, Early August, and Late August

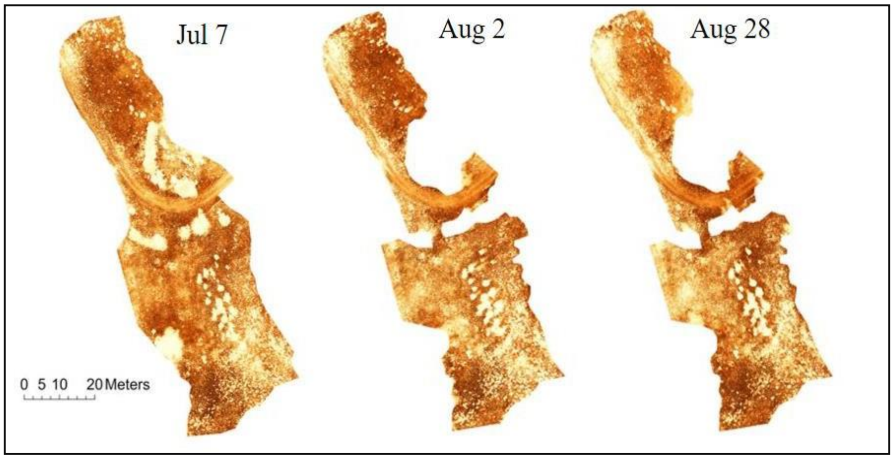


Figure 13: SIM-ME-541 Percentage Dead Cover Maps from Early July, Early August, and Late August

3.3 Classification Maps

SIM-AD-027:

Vegetation species and abundance (Figure 14) experienced distinct changes during the growing season. In May, the site was 57% grass, with the remainder either dead material or soil. However, in July the amount of green vegetation increased, especially the number of native flowing plants. The presence of goldenrod persisted during the growing season.

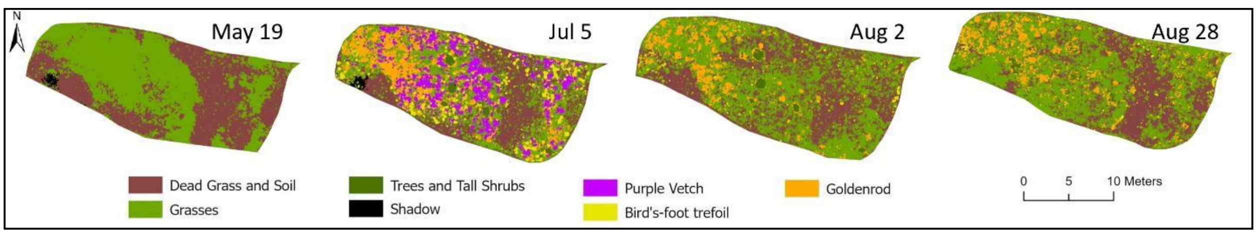


Figure 14: Classification maps for site SIM-AD-027 showing the change in vegetation throughout the spring and summer.

SIM-AD-545:

In early May, the site (Figure 15) was mostly composed of soil, rock and dead material with grasses and trees making up less than 18% of the site. In July, vegetation filled out the eastern half of the site, while the western half remained baren. This was likely due to the western half having poor, rocky soil and at a higher elevation than the eastern half. Vegetation species diversity was lower than what was observed at site SIM-AD-027.

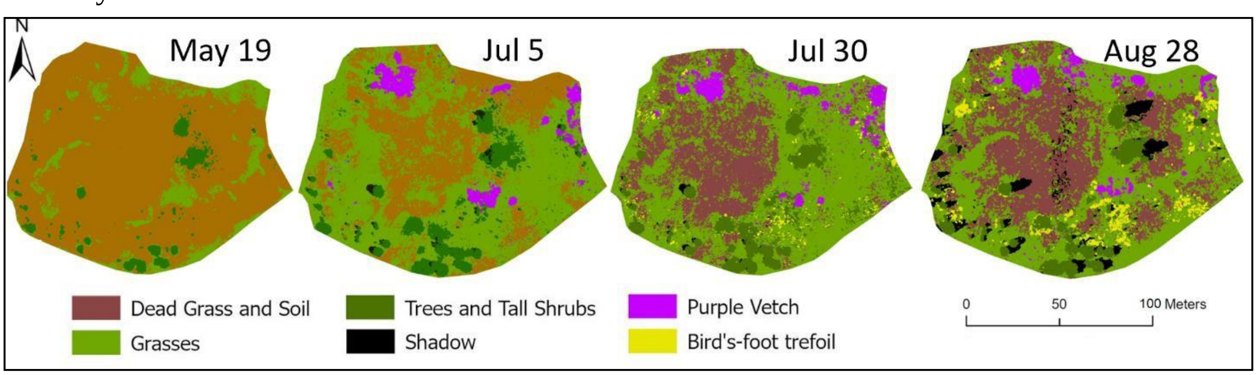


Figure 15: Classification maps for site SIM-AD-545 showing the change in vegetation throughout the spring and summer.

SIM-ME-541:

Many rocks and mosses were found at this site throughout the months of July-August and highlighted the difficult growing conditions due to dry soil (Figure 16). The amount of dead vegetation seen before the July growing season was missing from this site. Throughout the growing season, the amount of grass remained consistent, with small patches of flowering plants observed in the North and South ends of the site.

Figure 16: Classification maps for site SIM-ME-541 showing the change in vegetation throughout the spring and summer.

4. Summary

4.1 Conclusions

Drone imaging is an invaluable tool, providing a wealth of information with spatial and temporal details for the selected field sites. Our mapping results indicate that drone images can effectively capture key ecological parameters including species diversity and vegetation factional cover dynamics in the three sites.

- *Species Diversity Dynamics:* One of the significant advantages of employing drone imaging is its ability to capture temporal variability in species diversity over a growing season. To ensure a comprehensive understanding, we conclude that the drone images need to be taken at least three times during the growing season in the study area. This strategic approach allowed for the documentation of shifts in species composition over the seasons, shedding light on the dynamic nature of ecosystems. By providing a bird's- eye view of the landscape, we were able to use the drone images to discern patterns and fluctuations in species diversity that may be overlooked through traditional ground-based methods.

- *Vegetation Cover Assessment:* To capture the maximum green cover, the drone must fly once during the peak growing season in July-August for the study area. This approach facilitated the precise documentation of the extent of the greenness, contributing essential information for understanding the health and vitality of the ecosystem.

- *Monitoring Dead Cover:* In tandem with assessing live vegetation, the drone can be deployed once in May to capture the percentage of dead cover. This critical metric aids in comprehending the overall health of the ecosystem, providing crucial insights into the ecological processes shaping the landscape. Further, if there is an opportunity to take images multiple times over the growing season, dead cover can be estimated to identify areas of potential stress or disturbance.

Soil Sampling: Large soil variability is observed for each of the selected sites. Soil moisture content was low in all sites, and varied within a site by up to 5X across locations. Soils were not in danger of acidification. Rather, some areas would be classified as too alkaline for optimal vegetation productivity. Soil organic matter was very low across all sites. It is likely that increasing organic matter would lower soil pH and increase the water holding capacity of the soils. Soils were not negatively impacted by heavy metal loads.

Soil Properties vs Invasive Species: Our data reveal a compelling linkage between poor soil properties and the increased prevalence of invasive species. Areas characterized by suboptimal soil conditions exhibited a higher percentage of invasive species colonization. This finding suggests the importance of soil health in shaping the ecological composition.

In conclusion, drone imaging and image processing techniques have proven to be a transformative approach for fast assessment of vegetation conditions in rehabilitated sites, enabling a more complete understanding of species dynamics and vegetation cover. However, field observations and sampling remain essential for soil variability assessment.

4.2 Recommendations

To strengthen the validity of our findings but also enhance the practical applications of fast site assessment, there is a need for continued fieldwork, expanded datasets, testing of workflows, and a deeper exploration of soil-vegetation relationships.

Expansion of Study Sites: By visiting more field sites with a broader range of ecosystems and species, we aim to improve the algorithms' ability to accurately identify and categorize different vegetation types and ecosystem conditions. This expanded dataset will contribute to more robust mapping models.

Collection of More Field Data: To confirm our findings, especially regarding the optimal number of field visits required for assessing dead or green fractional cover, determining species composition, and capturing soil temporal variability, it is crucial to conduct additional fieldwork from better-designed transects and field plots.

Thorough Workflow Refining and Testing: The current workflow has shown promise, but its efficacy needs to be rigorously tested and further improved under diverse conditions. Further refinement and testing of the workflow could consider placing designated ground-control points, standardizing flight paths, assessing the oblique angle's impact, and examining the usefulness of multispectral and thermal images. These are essential to establish a reliable and standardized process for drone remote sensing in vegetation assessment.

Exploration of Soil-Vegetation Relationships: To gain a comprehensive understanding of the ecosystem, it is crucial to further evaluate the need for seasonal changes in soil properties. This will also support the exploration of the relationships between variability in soil properties, and vegetation spatial and temporal patterns. By exploring these connections, we can refine our analysis and contribute to a more complete understanding of the factors influencing the observed patterns.

Investigation of Temporal Trajectories: Each of the above recommendations needs to be applied over a longer timeframe than a single growing season. By studying more sites over longer terms with the improved methodology we can further improve the algorithm's accuracy. Seasonal changes in weather patterns affect community assemblages year over year, and the detection of species from drone imagery in relation to weather data will improve the predictability of future vegetation changes. Additionally, the expanded monitoring will allow for an increased understanding of the development trajectory of the rehabilitated sites, which will further aid in the refinement of not only a rapid assessment protocol but also an improved site rehabilitation protocol.

Acknowledgements

Funding from The Ontario Aggregate Resources Corporation supported this project. We appreciate the site owners for their support of this project. Thanks also goes to the drone pilot Peter Ge and many students in Professor Yuhong He and Professor Tim Duval's labs who support data collection and analysis. Kaeley Curran and Clara Dunlop, technicians with TOARC, are also thanked for their assistance in the field. In addition, we also appreciate Professor Marc Johnson in the Department of Biology at the University of Toronto Mississauga for helping us identify species.

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