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Using Unmanned Aerial Vehicles to Quantify Erosion Control Measures on a Reclaimed Central Utah Coal Mine

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USING UNMANNED AERIAL VEHICLES TO QUANTIFY EROSION CONTROL

MEASURES ON A RECLAIMED CENTRAL UTAH COAL MINE

by

Christopher R. Brown

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ABSTRACT

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by

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Utah State University, 2021

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For certain landscape reclamation efforts, the Utah Division of Oil Gas and Mining (UDOGM) utilizes a deep gouging technique called "pocking". The process of pocking establishes closely spaced gouges approximately 1.2 meters in diameter and 0.5 meters deep across a reclaimed landscape in order to reduce surface erosion and promote plant growth on steep terrain in arid regions. Pocks are designed as a series of micro watersheds that trap water to aid in plant establishment and reduces overland flow of water. Over time vegetation grows within the pocks as they infill with sediment. While this method is considered an effective reclamation technique, its effectiveness has, to date, relied on anecdotal observation only. This research will utilize consumer grade unmanned aerial systems (UASs) commonly known as "drones", to develop a technique by which pocks can be monitored and the effectiveness of pocking can be quantified. To this end, UAS overflights spanning two years (2019-2020) resulted in high-resolution (2.5cm) ortho imagery as well as digital terrain data at the same resolution. A comparison of the data collected across these two years identified erosion and deposition within and between pocks as well as the establishment and spread of seeded vegetation. The results also identified a spatial pattern of landscape subsidence as the reclaimed landscape settled. We found that, with effective geographic control, low-cost, off-the-shelf, consumer grade UASs are an effective tool to monitor and quantify changes in reclaimed landscapes.

(72 Pages)

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For certain landscape reclamation efforts surrounding, the Utah Division of Oil Gas and Mining (UDOGM) utilizes a surface roughing technique called "pocking". The process of pocking establishes closely spaced gouges approximately 1.2 meters in diameter and 0.5 meters deep across a reclaimed landscape in order to reduce surface erosion and promote plant growth on steep terrain in arid regions. Pocks are designed as a series of micro watersheds that trap water to aid in plant establishment and reduces overland flow of water. Over time vegetation grows within the pocks as they infill with sediment. While this method is considered an effective reclamation technique, its effectiveness has, to date, relied on observation only. This research will utilize consumer grade unmanned aerial systems (UASs) commonly known as "drones", to develop a technique by which pocks can be monitored and the effectiveness of pocking can be quantified. To this end, UAS overflights spanning two years (2019-2020) resulted in high-resolution (2.5cm) ortho imagery as well as digital terrain data at the same resolution. A comparison of the data collected across these two years identified erosion and deposition within and between pocks as well as the establishment and spread of seeded vegetation. The results also identified a spatial pattern of landscape subsidence as the reclaimed landscape settled. We found that, with effective geographic control, low-cost, off-the-shelf, consumer grade drones are an effective tool to monitor and quantify changes in reclaimed landscapes.

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CONTENTS

Page

Abstract ... iii

Public Abstract ... v

Acknowledgments ... vii

Contents ... viii

List of Tables ... x

List of Figures ... xi

1. Introduction ... 1

1.1. Historical Mining in Utah ... 2
1.2. Environmental Regulation on Mining ... 2
1.3. Reclamation ... 3
1.4. Pocking ... 4
1.5. Unmanned Aerial Systems ... 6
1.6. Photogrammetrically Derived Topography vs. LiDAR ... 7

2. Study Area ... 8

2.1. Cottonwood/Wilberg Mine ... 9
2.2. Des Bee Dove Mine ... 10

3. Methodology ... 12

3.1. UAS Data and Processing ... 12
3.2. Flight Data Processing ... 14
3.3. Ground Control ... 15
3.4. LiDAR ... 17
3.5. Ground Monitoring Data ... 18
3.6. Vegetation Monitoring ... 22
3.7. Pock Delineation ... 23
3.8. Change Detection ... 25

4. Results ... 26

4.1. Site maps ... 26
4.2. Pocking Tool ... 34

4.3. Ground Change Detection..36
4.4. Areas of Interest..37
4.5. Vegetation (NDVI) 44
4.6. Ground Evaluation: Erosion 45
4.7. Ground Evaluation: Vegetation 49

5. Discussion 50

6. Conclusion 52

7. References:..53

LIST OF TABLES

Page

Table 1: Flight Parameters in Pix4Dcapture 13

Table 2 Seed mix used at the Cottonwood Reclamation site 22

Table 3: Ground Control Point elevations and differences for both May overflights 37

LIST OF FIGURES

Page

Figure 1: Pocked slope at the Deer Creek Coal Mine reclamation site, Emery County, Utah....................4

Figure 2: A single pock located at the Deer Creek Coal Mine reclamation site, Emery County, Utah....................4

Figure 3: Pocks retaining water after a storm....................5

Figure 4: Project site locations within Emery County, Utah, United States of America.....8

Figure 5: Cottonwood Reclamation site in May 2019....................9

Figure 6: Des Bee Dove Reclamation Site 2017....................11

Figure 8: DJI M210 Drone (Dronefly,2020)....................12

Figure 8: Phantom 4 Pro (Gizmochina, 2018)....................12

Figure 9: First flightpath over the lower part of Cottonwood in Pix4Dcapture....................13

Figure 11: Digital surface model of the Cottonwood site....................14

Figure 11: Orthomosaic of the Cottonwood Reclamation site....................14

Figure 12: Location of all boulder ground control points across the Cottonwood site......15

Figure 13: Ground control point selection between the original May, 2019 imagery and a subsequent overflight. 16

Figure 14: 3-dimentional rendition of ground-based 2018 Lidar Data.....................17

Figure 15: Terrestrial LiDAR derived DSM with no interpolation....................18

Figure 16: Ground verification points, and sediment staffs.....................19

Figure 17:Evaluation of erosion at the bottom of a pock....................20

Figure 18:Rebar sediment staff....................20

Figure 19:Typical evidence seen of the sloughing of pock walls found across the site....21

Figure 20: Normalized Difference Vegetation Index Equation. 23

Figure 21:: NDVI comparison to its multispectral imagery 23

Figure 22: The workflow of the pock delineation in ESRI ArcMap Model Builder. 24

Figure 23: Pocking tool delineation output..24

Figure 24: Outline of the mutual overlap between drone flights at the Cottonwood site 27

Figure 25: Cottonwood orthomosaic image for May 2019. The northwest arm of the canyon was not covered due to inability to safely collect enough overlapping images of the terrain while avoiding the canyon walls. 28

Figure 26: Cottonwood orthomosaic image from May 2020. Collected using identical flight parameters used for the May 2019 flight 29

Figure 27: Cottonwood orthomosaic image from June 2019. This image was collected at a higher flight elevation compared to other flights using flight planning software that integrated a digital elevation model to maintain a standard height above ground and thus avoid cliff faces. 30

Figure 28: The June 2019 multispectral image orthomosaic collected by the UDOGM...31

Figure 29:Des Bee Dove Ortho-image from August 2019 flights by UDOGM................32

Figure 30:MultiSpectral Imagery collected from an August 2019 flight by UDOGM 33

Figure 31: Pock evaluation over the central part of the Cottonwood site..........................34

Figure 32: Pocking tool output for the Des Bee Dove mine showing the general weathering of pock structure over time with aerial imagery and a shaded relief. 35

Figure 33:Ground change map created by subtracting the 2019 DSM from the 2020 DSM. Red areas indicates lower elevation in 2020 and green areas higher elevation in 2020. 36

Figure 34: Areas of Interest labeled in order of discussion 38

Figure 35: General Erosion at AOI 1. Erosion from pock walls can be seen, with no change or increase in depth being seen at the center of the pocks....................................39

Figure 36: Pocks coalescing and elongating as they infill and erode 40

Figure 37: Shaded relief showing pocks filling over time at AOI #2 from 2019 to 2020 40

Figure 38: Vegetation giving a false signal in the change detection at AOI #4 41

Figure 39: False signal from tumble weeds at AOI #3 41

Figure 40: Area of extreme settling at AOI # 5 42

Figure 41: Area rising attributed to erosion from adjacent, unpocked landscape. 43

Figure 42. Vegetation growing within pocks at the Cottonwood site as identified by the NDVI....44

Figure 43. Vegetation identified by the NDVI at the Des Bee Dove site. 44

Figure 44: Erosion along the pock walls can be seen in the central and far pocks. 45

Figure 45: Variation of the pock material across the site inhibited a consistent method to evaluate sedimentation at the bottom of the pocks. 46

Figure 46:Example of using the ground images and aerial imagery to correlate locations and correct sediment staff GPS points, with red and blue circles corresponding to each other across the images 46

Figure 47: Ground verification of infilling pocks from AOI #2 47

Figure 48. Top Left- The pock outlines overlaid on the DSM change map, showing an area assumed to be a DSM error. Top Right- Aerial imagery of location, showing a ridge formation at the same site. Bottom- The erosion/subsidence event verified on the ground 48

Figure 49. Vegetation growing in separate pocks at Cottonwood in 2019 (Left) and 2020 (Right) 49

1. Introduction

The Utah Mined Land Reclamation Act of 1975 states that “mined land should be reclaimed so as to prevent conditions detrimental to the general safety and welfare of the citizens of the state and to provide for the subsequent use of the lands affected”. To this end, the Act stipulates that “all mining in the state shall include plans for reclamation of the land affected”. The goal of reclamation efforts is to return disturbed land to a stable and productive state (Goldstein & Smith, 1975; Kahn et al., 2001; Otto, 2010).

An important goal of land reclamation is the control of surface erosion and subsequent deposition of soil on the surrounding landscape (Loch, 2000; Martín Duque et al., 2015). The success of a reclamation project is typically determined by successful establishment of vegetation, which helps maintain soil stability (Holl et al., 2018; Martínez-Ruiz et al., 2007; Shen et al., 2017). Land reclamation activities have used various erosion control techniques to stabilize slopes and reduce erosion (J. M. Grace III et al., 1998; Liu et al., 2019; Montoro et al., 2000).

In Central Utah, the Utah Division of Oil Gas and Mining (UDOGM) has utilized a specific deep gouging erosion mitigation technique called “pocking” (Utah Oil Gas and Mining, 2000). The UDOGM considers pocking to be an effective reclamation method that promotes plant growth and reduces erosion on steeper slopes, but the benefits of pocking have not yet been quantified by the UDOGM. Similar techniques such as deep gouging, dozer basins, and soil ripping have been evaluated by others with mixed results (Ferguson, 1985; Lewis Peter Jennings, 1980; Lyle Andrew King, 1980; Scholl, 1985; Schuman, 1984). The primary objective of this thesis is to evaluate the ability for unmanned aerial systems (UAS) to monitor and assess the effectiveness of pocking as a technique to reduce erosion and promote vegetation growth. A secondary objective is to develop a methodology that the UDOGM can use to monitor these landscapes over time using Unmanned Aerial Systems (UAS).

1.1. Historical Mining in Utah

The reclamation of land disturbed by mining and other human activities has become a more common practice in the 20th century (Otto, 2010). In Utah, mining began almost immediately after the first settlers arrived in 1847. Coal was discovered in 1850, and the first coal mine opened in 1854 (Sutton, 1949). Shortly after the railroad came to Utah in 1869, mining quickly expanded across the region. By 1912, hundreds of millions of dollars of gold, silver, copper, coal, iron, zinc, lead, and other minerals had been extracted. In 2018, the mining industry in Utah generated approximately $3.7 billion in revenue (Mills et al., 2019). Yet the success of the mining industry throughout Utah's post-European settlement history has resulted in over 17,000 abandoned mines with little or no reclamation. Prior to 1975, mines in Utah could be abandoned without notice, and mine owners had no legal responsibility to mitigate human safety or environmental impacts resulting from these abandoned mines.

1.2. Environmental Regulation on Mining

During the 1960's and '70's, growing concern for the environmental health of land, air, and waterways across the United States led to multiple environmental laws enacted by the federal government, as well as most States. Many of these laws, such as the Clean Air Act (Clean Air Act, 1970) and the Clean Water Act (Clean Water Act, 1972) directly and indirectly impacted mining and industrial production across the nation.

“The Surface Mining Control and Reclamation Act of 1977” (Public Law 95-87) was enacted by Congress to address specific concerns over environmental impacts of historical and active coal mining and the post-mining reclamation of coal mines nationwide. This was done by defining reclamation expectations for closed coal mines and imposing taxes on coal production to fund reclamation of coal mines abandoned before the law was enacted (Surface Mining Control and Reclamation Act of 1977, 1977). In 1975, the state of Utah passed the “Utah Mined Land Reclamation Act” to manage all mining and mine reclamation throughout the State. This act stipulated that while mining is “essential to the economic and physical well-being of the state of Utah and the nation,” it was now required that “all mining in the state shall include plans for reclamation of the land affected” (Utah Mined Land Reclamation Act, 1975)

1.3. Reclamation

With post-mine reclamation becoming a mandated practice, mine owners were required to develop reclamation plans. The federal and state land reclamation acts require that where ground is disturbed by mining operations, the operator must restore the site to a semi-natural landscape once mining operations have completed (Otto, 2010; Surface Mining Control and Reclamation Act of 1977, 1977). A key part of any reclamation effort is preventing surface erosion and the transportation of sediment off site or into waterways. Containing soil within the reclaimed area is typically done by using man-made structures designed to retain soil and help vegetation establish (*Annual Evaluation Summary Report for the Regulatory Program Administered by the State of Utah*, 2007; Martín Duque et al., 2015; Martínez-Ruiz et al., 2007; Martínez-Ruiz & Fernández-Santos, 2005; Moreno-de las Heras et al., 2008; Rovis-Hermann et al., 2002; Wantzen &

Mol, 2013; Zhang et al., 2014). The effectiveness of any erosion control method is determined by its ability to control sediment movement due to a defined amount of rainfall, snowmelt, and/or wind. The success of an erosion prevention method also depends on site characteristics such as soil type, slope, and scale to which the erosion control system is built (Babcock & McLaughlin, 2013; Martínez-Ruiz & Fernández-Santos, 2005; Martín-Moreno et al., 2016; Rickson, 2006; Romanek et al., 1994).

1.4. Pocking

To manage erosion on reclaimed lands in Central Utah, the Utah Division of Oil Gas and Mining within the Utah Department of Natural Resources has, over the past 20 years, utilized a deep gouging erosion control method referred to as "pocking" (C. A. Semborski et al., 2006; Utah Oil Gas and Mining, 2000). Pocks are created using an excavator which digs gouges at least half a meter deep and up to 1.2 meters wide across the reclaimed area. The soil from that hole is placed downslope of the gouge, and the process is repeated with pocks distributed in a semi-random, adjacent pattern across the slope (Figures 1 and 2).

Figure 1. Pocked slope at the Deer Creek Coal Mine reclamation site, Emery.

Figure 2. A single pock located at the Deer Creek Coal Mine reclamation site,

Pocks are designed to control overland runoff by effectively reducing the slope length and collecting water. Each individual pock acts as a small catchment basin to trap water (Figure 3) and provide moisture to help establish seeded vegetation. The UDOGM regards this method as an effective erosion control technique that encourages vegetation regrowth, but its effectiveness has never been quantified. The UDOGM has relied on anecdotal observation supported by limited vegetation and sediment measurements produced by bond release requirements. Due to this anecdotal observation and limited field sampling, mine operators have been discussing the possibility that pocking could eliminate the requirement for sediment catchment ponds commonly placed at the topographic “pour point” of the landscape. The intent of these ponds are to prevent sediment from exiting the site, which pocking appears to accomplish. To this end, a recent reclamation site at the Cottonwood coal mine in Emery County, Utah used pocking as the sole method of erosion control. Though pocking is regarded as an effective technique, the lack of an empirical evaluation of how pocks and their distribution across

Figure 3. Pocks retaining water after a storm.

the landscape affect erosion processes and influence vegetation growth is a critical gap in the knowledge base. A hindrance to quantifiably evaluating pocking is that repeated field measurements to assess erosion and vegetation dynamics can be hazardous due to the rough nature of the pocked landscapes, is time consuming, expensive, and frequent foot traffic through a pocked landscape can degrade the pock "walls", reducing their effectiveness.

1.5. Unmanned Aerial Systems

Unmanned aerial systems (UAS) also known as drones, have been used to quickly gather cost-effective, high-resolution imagery that can be converted to topographic data as well as interpreted to extract vegetation data (Gillan et al., 2017; Xue & Su, 2017). These systems are used to collect imagery for historical documentation, site mapping and evaluation, photogrammetric extraction of topography, and can also carry various other sensors such as thermal imagers and light detection and ranging (LiDAR) systems (Amon et al., 2015; Gillan et al., 2017; Jozkow et al., 2016; Thompson, 2018). Drone acquired data can better enable managers to evaluate site conditions safely and effectively (Adams et al., 2016; Georgopoulos et al., 2016; Papakonstantinou et al., 2017).

The primary objective of this project is to evaluate the ability of common, off-the-shelf UASs to measure and monitor erosion as well as vegetation growth across a pocked landscape. To meet this objective, we used the recently reclaimed Cottonwood mine site in central Utah to measure topographic change within and between pocks, as well as to map where vegetation has reestablished. This site is compared to a geographically adjacent site that has undergone a similar pocking procedure in 2004.

1.6. Photogrammetrically Derived Topography vs. LiDAR

Light detection and ranging (LiDAR) is a data collection method where lasers determine the xyz location of points along surfaces surrounding the sensor (Lefsky et al., 2002). LiDAR can be deployed from both aerial and terrestrial platforms and is currently the best method capable of penetrating vegetation canopies to estimate ground elevation. For this reason, digital surface models (DSM's) derived from LiDAR are considered superior to those derived from photogrammetric methods. However, LiDAR is more expensive and complex to work with. While our reclamation sites are initially barren, and slowly gain canopy cover as the vegetation recovers, photogrammetric point clouds derived from imagery can be effectively used to map terrain (Jozkow et al., 2016; Passalacqua et al., 2015). As vegetation cover increases, the ability to penetrate vegetation canopy would make LiDAR a preferred solution for monitoring reclamation sites.

2. Study Area

The project's two reclamation sites are located in the higher elevation canyons northwest of the town of Orangeville in Emery County, Utah (Figure 4). Central Utah has a semi-arid climate with an average precipitation of 20cm per year (U.S. Climate Data, 2020).

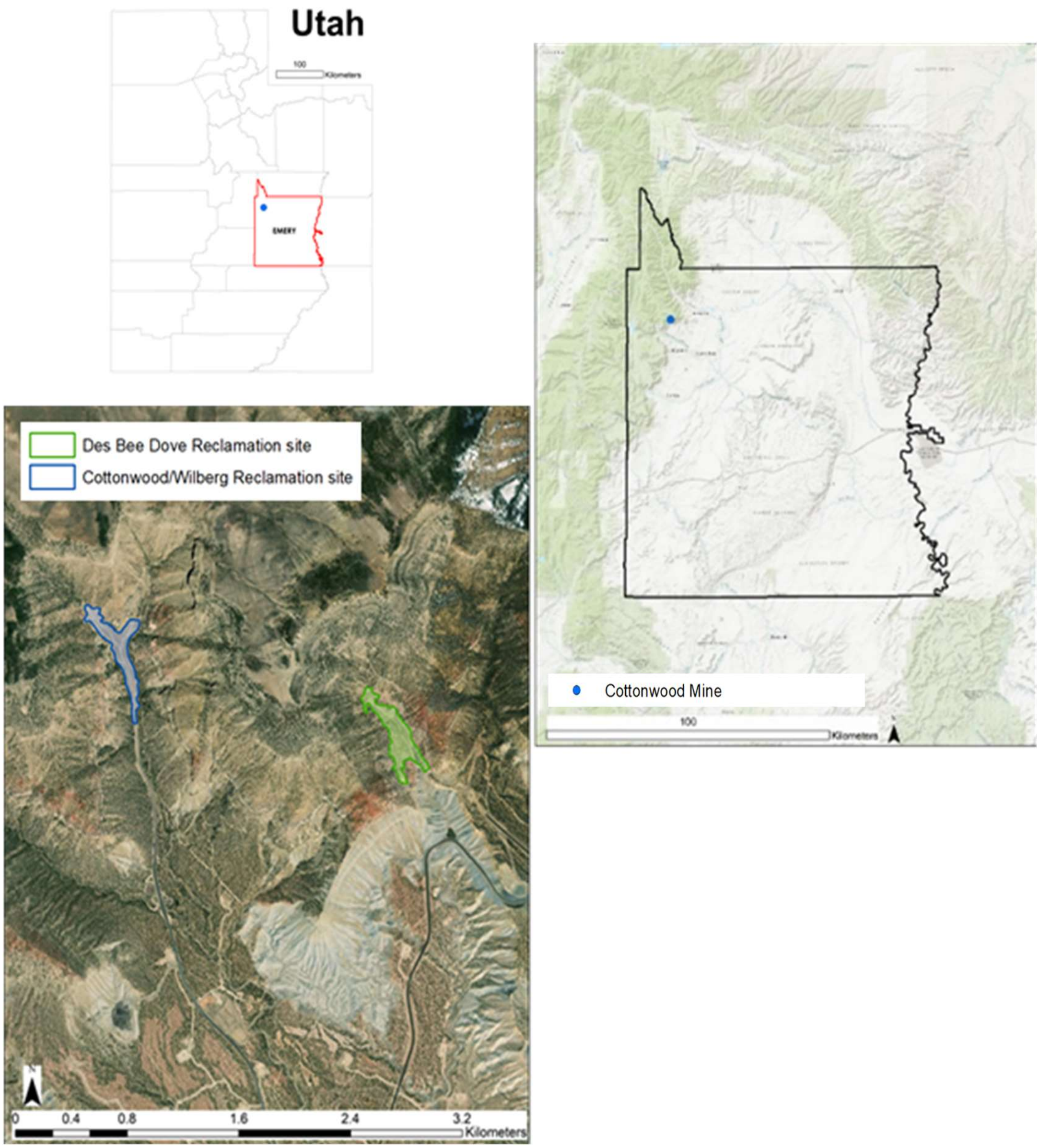

Figure 4. Project site locations within Emery County, Utah, United States of America.

The study sites are located in the Wasatch Plateau Coal field, a region historically known for its coal production and where several coal mines still operate as of December 2019.

The study sites are located in a region dominated by a mix of pinyon juniper and sagebrush vegetation communities (Barker, 1982). Both sites are located within generally south-facing steep, narrow canyons with elevation ranging between 2100 meters and 2800 meters above sea level, with slopes of the reclaimed portion ranging between 4 and 25% (2º – 14º).

2.1. Cottonwood/Wilberg Mine

The Cottonwood/Wilberg mine (hereafter the Cottonwood site) owned by PacifiCorp, was an underground coal mine complex opened in the 1890s and in operation until 2001. Following the mine closure, reclamation activities began in 2017 and were completed in March of 2018 (Figure 5).

Figure 5. Cottonwood Reclamation site in May 2019.

The Cottonwood site sits within a narrow canyon that forks east and west midway up the reclaimed area. It has a surface disturbance area of approximately 8.5 hectares that spans the width of the canyon floor. Pocking combined with hydroseeding was used as the erosion control method. The site also has a riprap drainage channel 1.5 meters deep and 6 to 17 meters wide installed along the north-south extent and into each fork, allowing upslope water to flow through the site as well as capture sediments that reach the channel from the surrounding pocked landscape. The lowest elevation of the reclaimed area is 2188 meters above sea level (ASL), and the upper benches are over 2405 meters ASL. The reclamation starts at the road terminus (lowest elevation) of County Road 57, and stretches 874 meters up the west fork, and 727 meters up the east fork, with the reclaimed portion of the valley floor averaging 70 meters in width and a maximum of approximately 120 meters across the widest point.

2.2. Des Bee Dove Mine

The Des Bee Dove mine reclamation site, which was used to characterize the long-term effects of pocking, is located in an adjacent canyon 1.5 km east of the Cottonwood site. Des Bee Dove was owned and reclaimed by PacifiCorp in 2003 and is considered successfully reclaimed by the state of Utah, with its bond being released in 2014. The site is also 8.5 hectares in size and provides a more than 17-year example of what the Cottonwood site will develop into (Figure 6). The highest elevation of the reclaimed area is at 2280 meters, and the lower elevation is around 2100 meters. The site features a similar riprap sediment trap channel present in Cottonwood and ranges from 4 to 12 meters wide. The native vegetation composition and topography is similar to the Cottonwood site.

Figure 6. Des Bee Dove Reclamation Site 2017.

3. Methodology

3.1. UAS Data and Processing

Two UAV platforms were used for this project (Figures 7 and 8); the DJI – Phantom 4 Pro v2 (P4P), and the (DJI) M210 (M210). The P4P is a popular, low-cost commercial drone produced by Dà-Jiāng Innovations (DJI). It carries a 20-megapixel camera with a 1” CMOS sensor with a maximum field of view (FOV) of 84 degrees. The camera is equipped with an autofocus lens with a 1m minimum focal distance with an aperture range of f2.8 - f11.

Figure 7. DJI M210 Drone (Dronefly, 2020).

Figure 8. Phantom 4 Pro (Gizmochina, 2018).

The M210 was equipped with a DJI Zenmuse X5 16-megapixel camera, with a 4/3” CMOS sensor and aperture range of f1.7 - f16, as well as a MicaSense Rededge M (MicaSense, Inc) multispectral camera, which can record reflected light in the red, blue, green, near infrared (NIR) and red edge portions of the electromagnetic spectrum (MicaSense, 2017).

The data collection flight paths for the P4P were created using the Pix4Dcapture (Pix4D SA), and Map Pilot for DJI (Drones Made Easy) cell phone applications. The M210 flight path was created using the UgCS (SPH Engineering), desktop drone control software. All flight path applications generate overlapping flight lines based on user input and upload flight line data to the UAS (Table 1, Figure 9).

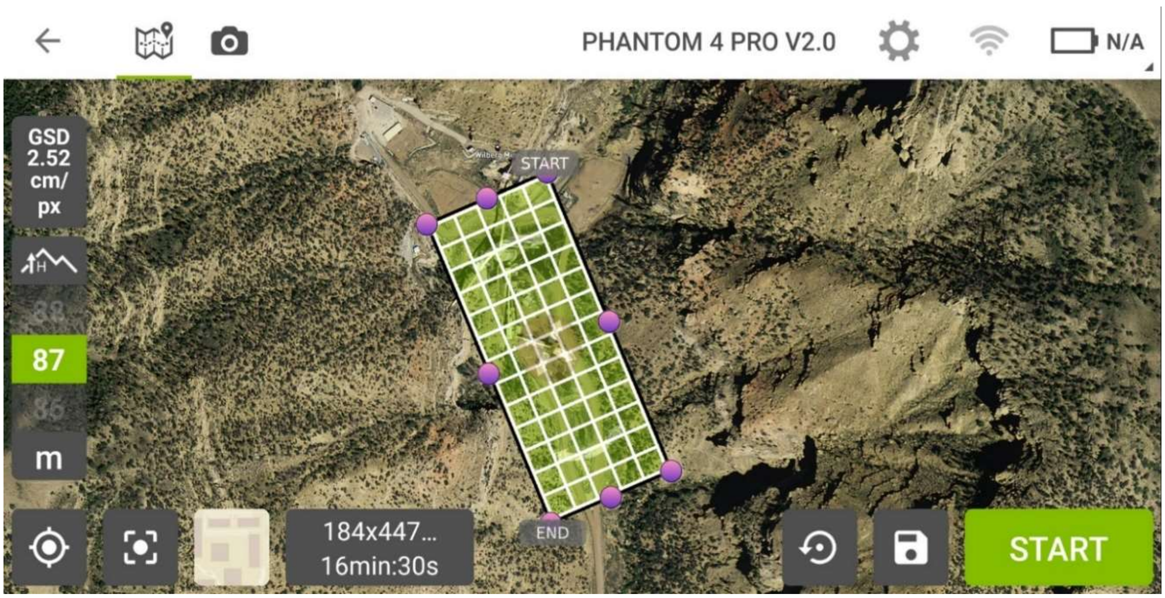

Figure 9. First flightpath over the lower part of Cottonwood in Pix4Dcapture.

Table 1. Flight Parameters in Pix4Dcapture.

Surface Resolution:	2.52cm/pixel
Flight Height:	87 meters
Camera Angle:	70°
Overlap between images:	80%

3.2. Flight Data Processing

Imagery collected after each overflight was processed using the commercially available structure from motion Pix4Dmapper photogrammetry software (Pix4D SA). For each overflight in May of 2019 and 2020, orthomosaic images were generated (Figure 10) with a ground resolution of 2.5cm (~1 inch), as well as a topographic point-cloud which was processed to a 2.5cm resolution digital surface model (DSM) of the site (Figure 11). All UAS collected imagery were projected to the Universal Transverse

Figure 10. Orthomosaic of the Cottonwood Reclamation site

Figure 11. Digital surface model of the Cottonwood site

Mercator (UTM) projection, using the North American Datum of 1983 (NAD83) as per the projection standard used by the state of Utah.

3.3. Ground Control

Both UAS platforms were controlled with GPS enabled positioning, as with all survey and most consumer grade UASs available today. Published specifications for the GPS nominal accuracies of the P4P and M210 are 1.5m horizontal and 0.5m vertical. These positional accuracies vary depending on local topographic relief and atmospheric conditions. Since the pixel resolution we targeted was 2.5cm, a nominal spatial error of

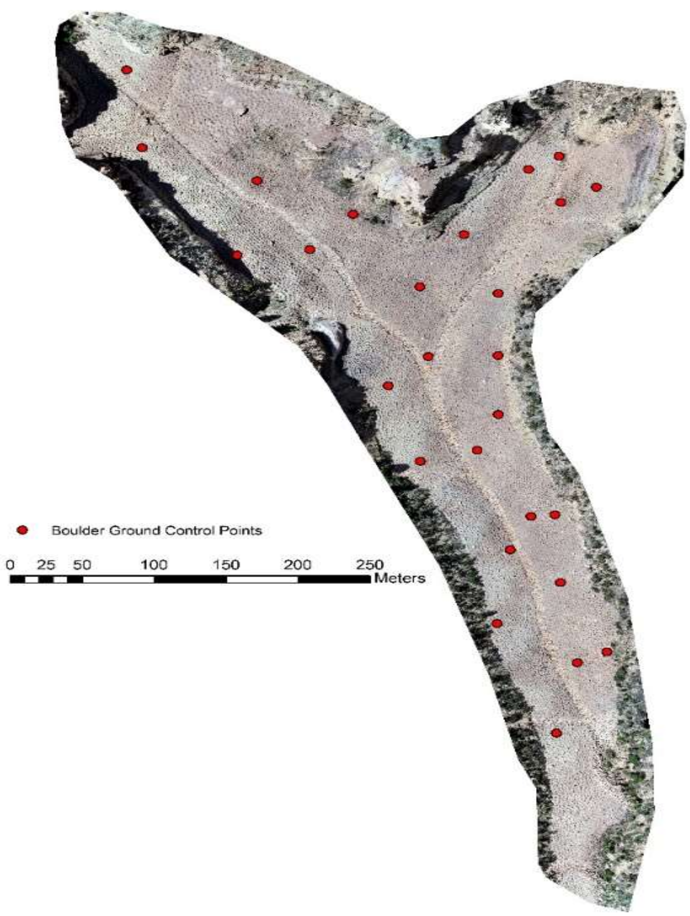

Figure 12. Location of all boulder ground control points across the Cottonwood site.

1.5m from the UAS GPS alone is too large. Typical UAS survey methods utilize ground control points (GCPs), whose geographic locations are recorded using survey grade GPS equipment, to increase the spatial accuracy of the imagery. The use of surveyed GCPs to correct for geographic error in processed UAS imagery can reduce spatial errors to within one cm depending on the equipment and location. Since we were collecting multi-date imagery to measure erosion as well as vegetation growth, the ideal process would have been to establish permanently placed GCPs to act as locational standards. This was not available at the Cottonwood site, and GPS signals were weak within the confines of the steep and narrow canyon walls.

Therefore, to geographically correct our multi-date imagery so that relative between-image spatial error was minimized, we identified a set of 27 GCPs from our initial imagery located at pronounced edges of large boulders that were distributed across the reclaimed surface (Figure 12 and 13). These boulders were a minimum of 1-2 meters in size and located on relatively flat surfaces so that their movement over our study time

Figure 13. Ground control point selection between the original May, 2019 imagery and a subsequent overflight.

would be minimal. All subsequent UAS data were processed using these 27 “permanent” GCPs to reduce horizontal and vertical spatial errors relative to the initial overflight

.

3.4. LiDAR

Ground-based LiDAR data were collected (Figure 14) by the United States Department of the Interior’s Office of Surface Mining Reclamation and Enforcement (OSMRE) under the direction of UDOGM in both the spring of 2018 and fall of 2019 using a Riegl LiDAR system (RIEGL Laser Measurement Systems GmbH). The LiDAR emitter was located at the same locations each year. LiDAR sampling locations were marked with rebar inserted into the ground.

Figure 14. 3-dimentional rendition of ground-based 2018 Lidar Data.

The intent of the ground-based LiDAR data was to form a baseline to monitor changes in pock depth over time. However, due to sensor look angles and the depth of individual pocks, the terrestrial LiDAR was unable to fully record the deeper portions of pocks requiring interpolation to create an artificial pock floor (Figure 15). However, these data were effectively able to identify pock ridgelines which provided a means to accurately map pock boundaries. However, evaluating pock depth over time is not possible using the ground-based LiDAR due to its inability to record actual pock depths.

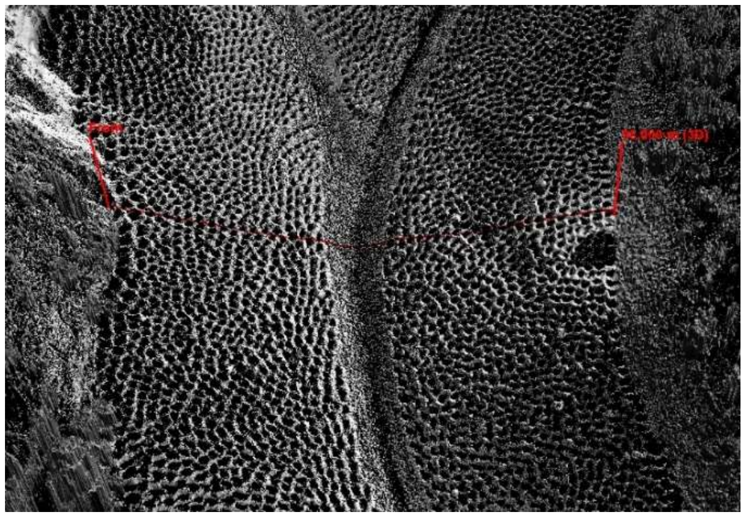

Figure 15. Terrstrial LiDAR derived DSM with no interpolation.

3.5. Ground Monitoring Data

Two field-based methods were used to validate data collected from the drone surveys. The first consisted of 100 randomly selected pocks (green points, Figure 16) sampled using a shovel to estimate sediment depth (Figure 17) during the Spring and Fall of 2019 and another 100 evaluated in late Spring of 2020. The second method consisted of 43 semi-permanent sediment staffs (Figure 18) installed during the random pock evaluations in 2019 (red points, Figure 16). Sediment staffs were placed in a series of somewhat evenly spaced transects spanning the elevational gradient of the canyon, with each transect running across the canyon. Rebar staffs were driven into the bottom of the pock and the protruding length of each stake measured with a ruler from the top of the rebar to the ground.

At each sampling location we measured erosional infilling of pocks as well as the amount of vegetation growth. The pocks sampled in 2019 were separated into 2 groups of 50 due to timing of field visits, with the first 50 being collected in the spring, and the second 50 in the fall. The points evaluated in 2020 were collected in May 2020, at the same time as the 2020 drone flight.

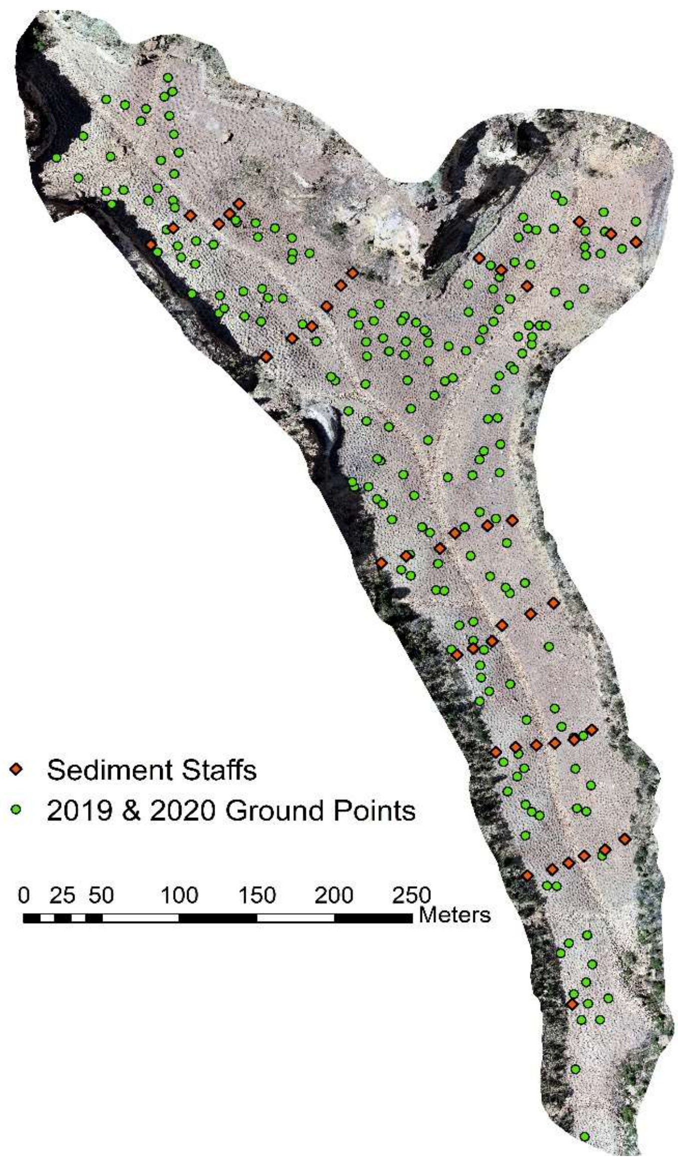

Figure 16. Ground verification points, and sediment staffs.

The location of each sampled pock was recorded with a field-grade GPS and for each pock we recorded the presence of vegetation, as well as a visual estimate of the area of the pock covered by vegetation. We also noted signs of visible erosion on the walls of the pock and estimated the amount of deposition at the bottom of the pock. To estimate deposition, a shovel was insert into the soil at the bottom of the pock to locate the original base of the pock by visually inspecting the sedimentation layers, and measuring the thickness of that layer (Figure 17). Inconsistencies in the material structure at the bottoms of the pocks (e.g. rocky or loose soil) created some uncertainty in the overall determination of the amount of soil deposited during the previous year. In many the sampled pocks there appeared to be little to no deposition from previous years. Most depositional evidence was due to sloughing or obvious erosion of the pock sides (Figure 19). These data were overlain onto the UAS derived data products to validate change measured by the digital surface models.

Figure 17. Evaluation of erosion at the bottom of a pock.

Figure 18. Rebar sediment staff.

Figure 19. Typical evidence seen of the sloughing of pock walls found across the site

3.6. Vegetation Monitoring

There were 14 different species of plants seeded during the reclamation work using a hydroseeder (Table 2). While the scope of this study did not include evaluating species composition within the pocks, the presence of vegetation was noted when evaluating the random pock samples and sediment staff pocks.

Table 2. Seed mix used at the Cottonwood Reclamation site

Common Name	Scientific Name	Equivalent PLS Lbs/Acre
GRASSES		
Western wheatgrass	*Agropyron smithii*	2
Bluebunch wheatgrass	*Agropyron spicatum*	3
Indian ricegrass	*Oryzposis hymenoides*	2
Needle and thread grass	*Stipa comata*	1
Thickspike wheatgrass	*Agropyron dasystachyum*	3
Basin Wildrye	*Leymus cinereus*	2
FORBS		
Blueleaf aster	*Aster glaucodes*	0.5
Small burnet	*Sanguisorba minor*	2
Lewis flax	*Linum Lewisii*	1
Palmer's Penstemon	*Penstemon palmari*	0.5
SHRUBS		
Serviceberry	*Amelanchier Alnifolia*	2
Fourwing saltbush	*Atriplex canescens*	2
Shadscale saltbush	*Atriplex confertifolia*	0.5
Big Wyoming Sagebrush	*Artemisia tridentate*	0.5
TOTAL		22

To evaluate the spatial distribution of vegetation growth, the UDOGM used a Micasense Rededge M sensor mounted onto their UAS and flown over the site on June of 2019. This provided a natural color (RGB) image as well as a Near Infrared (NIR) image. Using the NIR and red bands from the Micasense camera, we created a normalized difference vegetation index (NDVI) image map of the site (Figure 20 and 21). The NDVI is a common index used to measure the amount of photosynthetically active vegetation (Wang et al., 2001).

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + \mathrm{Red})}$$

Figure 20. Normalized Difference Vegetation

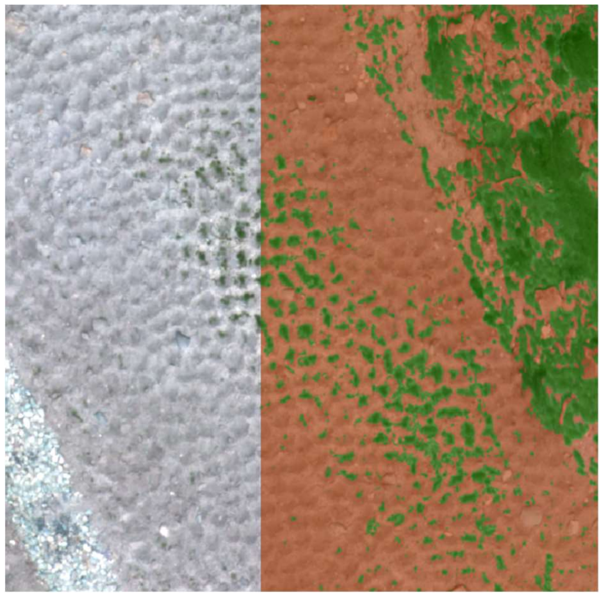

Figure 2126: NDVI comparison to its multispectral imagery.

3.7. Pock Delineation

To facilitate data analysis, individual pock boundaries were delineated for the entire Cottonwood reclamation site using the ground-based LiDAR data, as well as individual pock boundaries from the topographic data extracted from each overflight. Boundaries of the riprap channels placed along the drainage paths of the main and side canyons were mapped to exclude these areas from the pock boundary delineation process. To delineate individual pocks, a Python-based ArcGIS tool was developed to identify each individual pock as a unique basin (Figure 22).

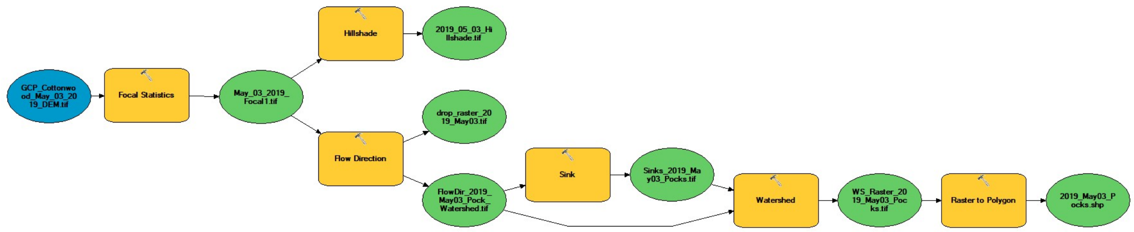

Figure 22. The workflow of the pock delineation in ESRI ArcMap Model Builder.

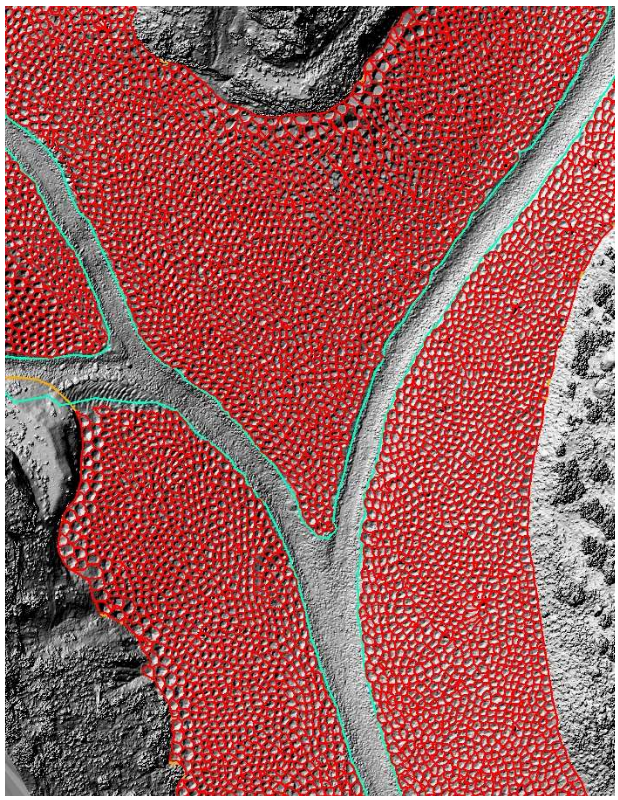

Figure 23. Pocking tool delineation output

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The UAS derived DSMs were smoothed using a 7x7 convolution filter to calculate the per pixel local mean elevation in order to reduce variation and mitigate the probability of developing “sub-basins” within each pock. Flow direction was calculated for the smoothed output to find the logical path of water across the raster values. Pixels where flow direction could not be assigned to a neighboring pixel (did not “drain” to any other pixel) were identified as “sinks”. These sink pixels corresponded to the bottoms of pocks. Sinks were then used as “seeds” to identify all pixels that drained to it and therefore delineating a “watershed” boundary for each individual pock. This resulted in a nearly complete delineation of pocks across the site (Figure 23).

3.8. Change Detection

A number of studies have used UAS derived topographic data to evaluate soil erosion and ground change (d’Oleire-Oltmanns et al., 2012; Gillan et al., 2017; Suh & Choi, 2017). To evaluate change in the depths of individual pocks, we used DSM data created from the May 2019, and May 2020 overflights of the Cottonwood study area. Both flights were conducted at approximately the same height above ground (83 meters), to target a nominal 2.5cm pixel spatial resolution. To evaluate soil erosion and deposition, the May 2020 DSM was subtracted from the May 2019 DSM. We evaluated error in the data sets by extracting the elevation difference between pixels for each of the 27 ground control points with the assumption that these points did not change in elevation between the two flights. Based on these 27 pseudo-invariant points, we estimated that the average absolute error between flights was 9cm.

4. Results

4.1. Site maps

Between the summers of 2019 and 2020, imagery from four UAS flights over Cottonwood, and one over Des Bee Dove were collected. From these flights, we used the Cottonwood imagery from May 2019 and May 2020 for the ground change comparison, and the multispectral imagery from Cottonwood June 2019 and the Des Bee Dove August 2019 for the vegetation evaluation.

Due to various complications with the drone flights, we were only able to obtain one flight of the entire Cottonwood site out of the three flights flown. This required us to crop our study area to exclude approximately .3 hectares at the bottom of the site, and 1.7 hectares at the top of the west fork. The remaining area of overlap between flights covered over 6 hectares of area within the main body of the site and the east arm (Figure 24).

High-resolution orthomosaics and DSMs were generated for each individual flight (Figures 25-28). The June 2019 Cottonwood and the August 2019 Des Bee Dove multispectral imagery were flown and processed by the UDOGM (Figures 28-30).

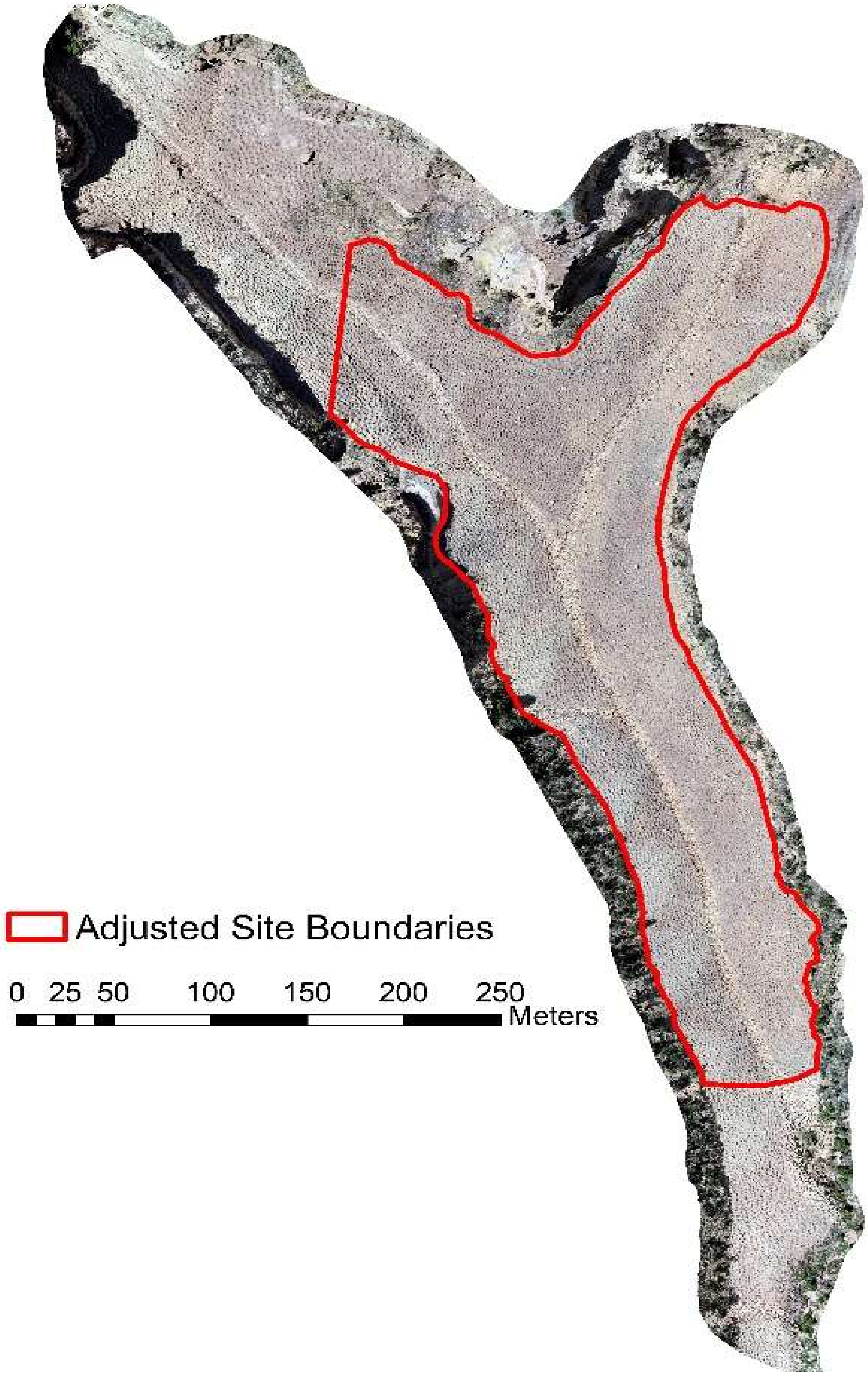

Figure 24. Outline of the mutual overlap between drone flights at the Cottonwood site.

Figure 25. Cottonwood orthomosaic image for May 2019. The northwest arm of the canyon was not covered due to inability to safely collect enough overlapping images of the terrain while avoiding the canyon walls.

Figure 26. Cottonwood orthomosaic image from May 2020. Collected using identical flight parameters used for the May 2019 flight.

Figure 27. Cottonwood orthomosaic image from June 2019. This image was collected at a higher flight elevation compared to other flights using flight planning software that integrated a digital elevation model to maintain a standard height above ground and thus avoid cliff faces.

Figure 28. The June 2019 multispectral image orthomosaic collected by the UDOGM.

Figure 29. Des Bee Dove Ortho-image from August 2019 flights by UDOGM.

Figure 30. MultiSpectral Imagery collected from an August 2019 flight by UDOGM.

4.2. Pocking Tool

The ArcGIS pock boundary tool was applied to the 2.5cm DSMs for each overflight to identify how the Cottonwood site surface has changed and to compared it to the Des Bee Dove site. The pocking tool output for the May 2019 Cottonwood flight shows a landscape with evenly distributed and relatively equally sized pocks (Figure 31). The Cottonwood site contained 11,086 individual pocks with an average pock area of $4m^2$ (StdDev: $1.5m^2$).

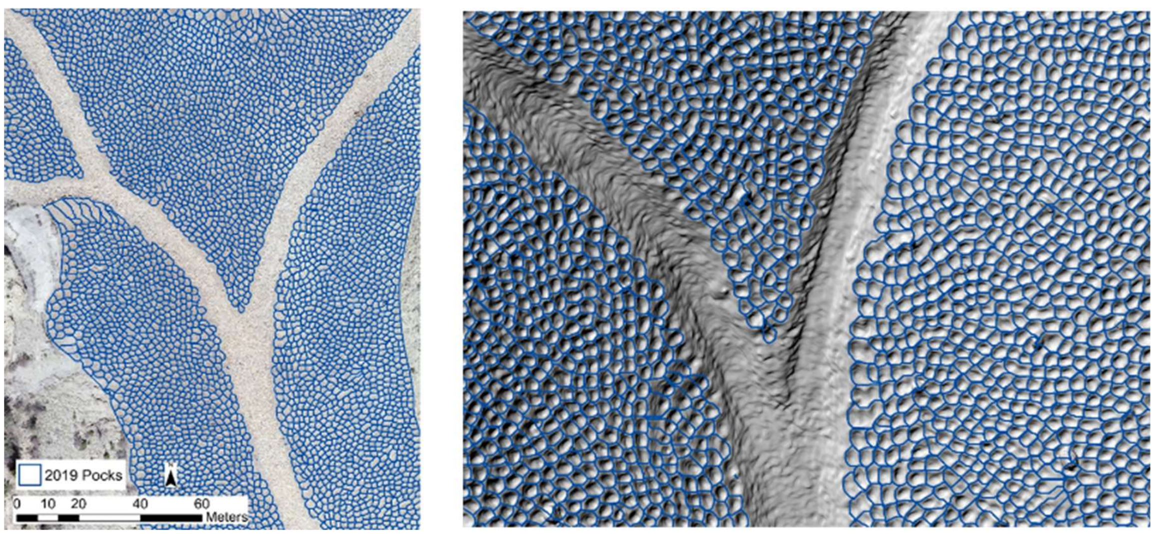

Figure 31. Pock evaluation over the central part of the Cottonwood site.

For the Des Bee Dove site, the pocking tool was unable to map distinct pocks due to weathering of pocks as well as vegetation growth which obscured pock boundaries. Remnant pocks did form longer, elongated “watersheds”, that flowed to the main drainage channel (Figure 32).

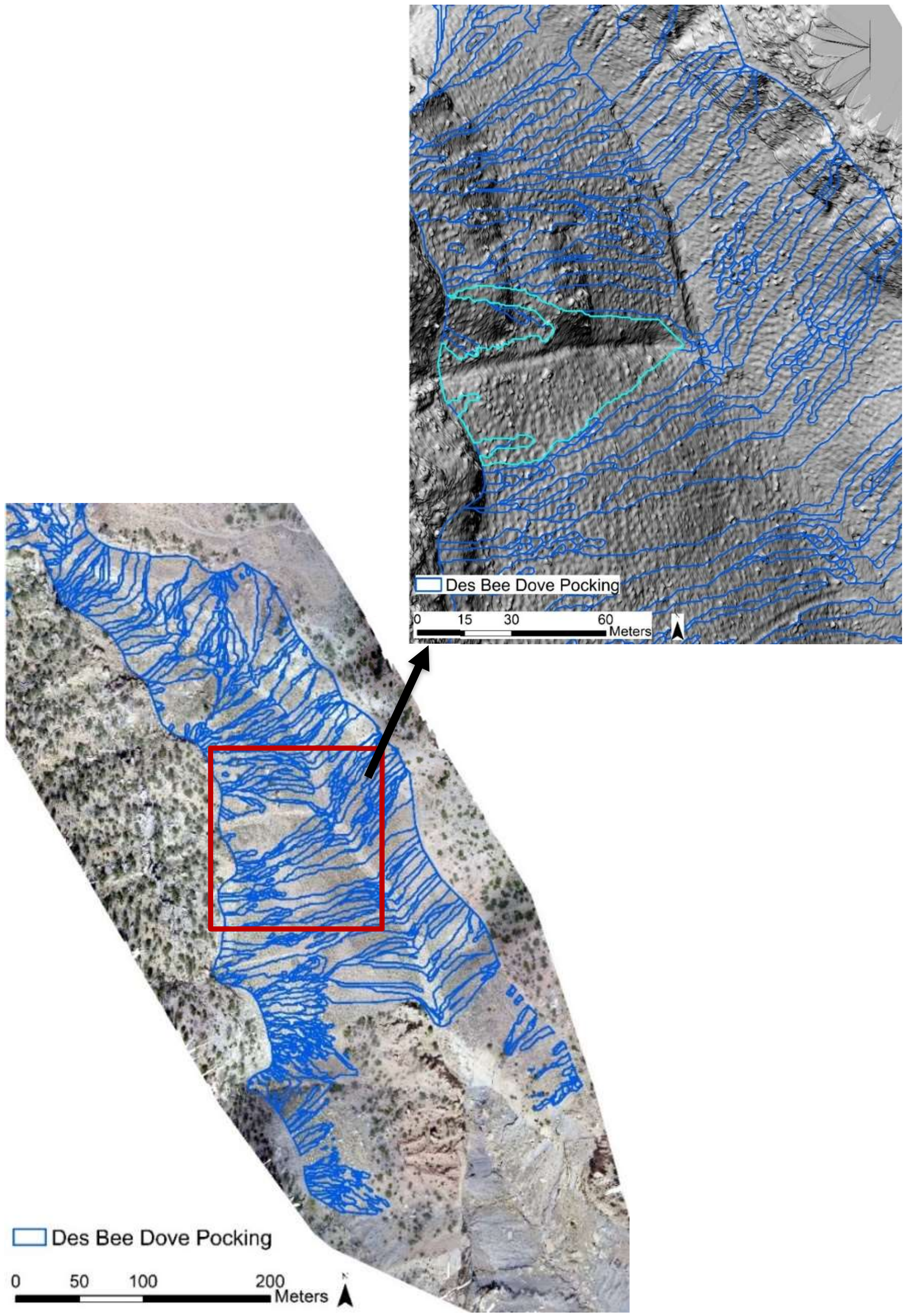

Figure 32. Pocking tool output for the Des Bee Dove mine showing the general weathering of pock structure over time with aerial imagery and a shaded relief.

4.3. Ground Change Detection

Subtracting the 2019 from the 2020 DSMs resulted in a ground change map (Figure 33). We visualized the change map by categorizing each measurement into 0.09m categories determined by the standard deviation of control point differences (Table 4). The color symbology corresponds to either an increase in elevation (yellow to green), or

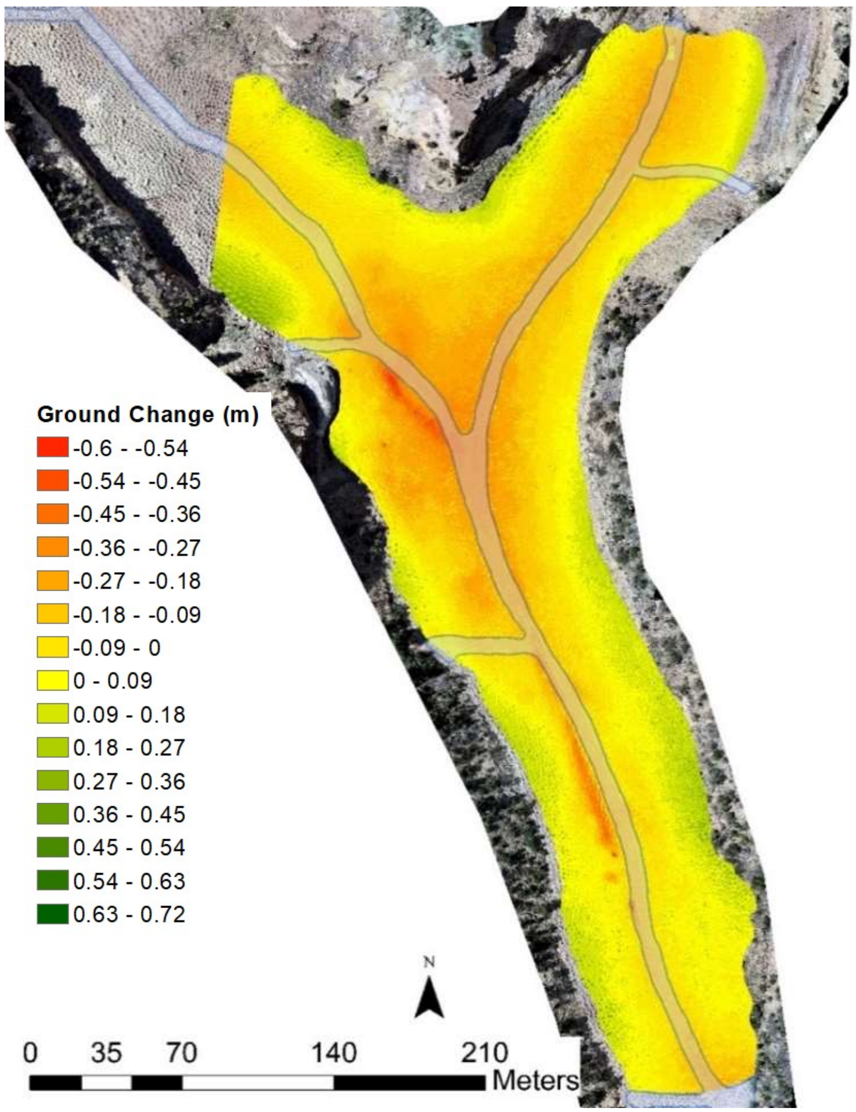

Figure 33. Ground change map created by subtracting the 2019 DSM from the 2020 DSM. Red areas indicates lower elevation in 2020 and green areas higher elevation in 2020.

a decrease (yellow to red) from 2019 to 2020. This ground change evaluation showed a substantial amount of decreased elevation in regions that surround the central drainage channels while most of the increases in elevation tend to be at the edges of the site.

Table 3. Ground Control Point elevations and differences for both May overflights.

GCP_ID	May_2019	May_2020	2020 -2019	Stdev
GCP3	2295.880	2295.880	0.000	0.09
GCP5	2284.020	2284.050	0.030	
GCP7	2277.620	2277.660	0.040	
GCP8	2268.600	2268.510	-0.090	
GCP9	2254.930	2254.840	-0.090	
GCP10	2262.810	2262.870	0.060	
GCP11	2268.410	2268.420	0.010	
GCP12	2275.710	2275.630	-0.080	
GCP13	2279.780	2279.720	-0.060	
GCP15	2277.180	2277.160	-0.020	
GCP16	2257.000	2256.810	-0.190	
GCP17	2251.970	2252.000	0.030	
GCP18	2256.340	2256.480	0.140	
GCP19	2247.540	2247.490	-0.050	
GCP22	2243.370	2243.420	0.050	
GCP23	2246.310	2246.450	0.140	
GCP24	2226.830	2226.830	0.000	
GCP25	2230.290	2230.440	0.150	
GCP26	2237.630	2237.640	0.010	
GCP27	2224.770	2224.820	0.050	

4.4. Areas of Interest

Figure 34 identifies six areas of interest (AOIs) that represent different areas of increased elevation (infilling), and areas of decreased elevation between 2019 and 2020. While decreases in elevation between the two years might signify surface erosion, we saw no evidence of significant surface erosion anywhere on the site.

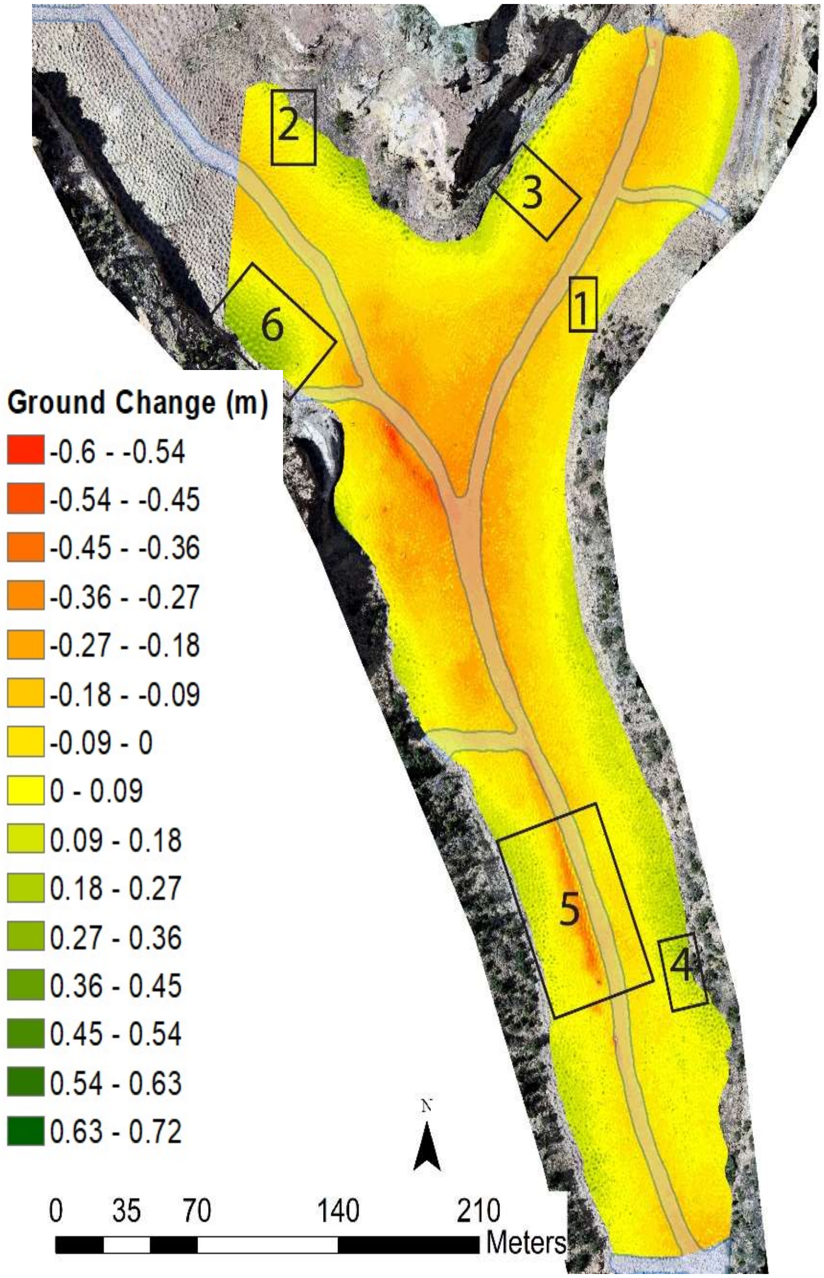

Figure 34. Areas of Interest labeled in order of discussion.

Area of Interest #1

Comparing the ortho imagery to the ground change map for this AOI, we can identify cause of change. Pock edges and sloped walls show increased erosion (negative values), while pock bottoms generally show slight infilling (positive values). (Figure 35)

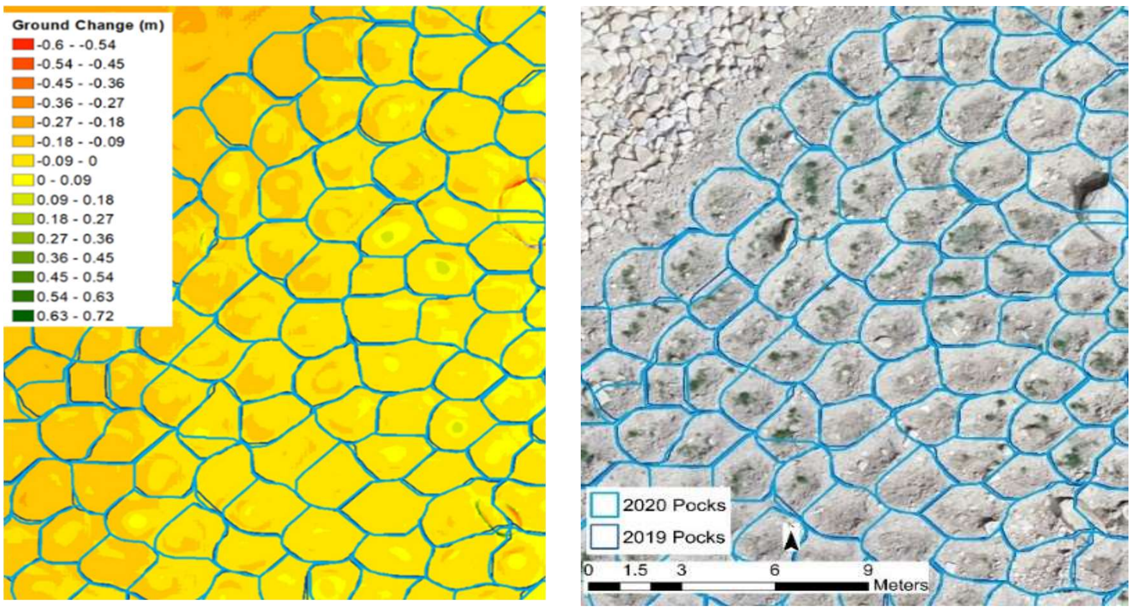

Figure 35: General Erosion at AOI 1. Erosion from pock walls can be seen, with no change or increase in depth being seen at the center of the pocks.

Area of Interest #2

AOI #2 shows greater infilling along the edge of the pocked landscape where we would expect increased overland flow from adjacent non-pocked areas. Additionally, pock boundary delineation using the 2020 imagery shows a pattern of coalescing pocks similar to what was observed at the Des Bee Dove site. This merging of pocks is found exclusively along the edges of the pocked landscape. These merging pocks are identified from the ground change evaluation and the aerial imagery confirmed what looked to be sediment change over the year (Figure 36). We can also identify the changed pocks using a shaded relief map of the site from the two years (Figure 37).

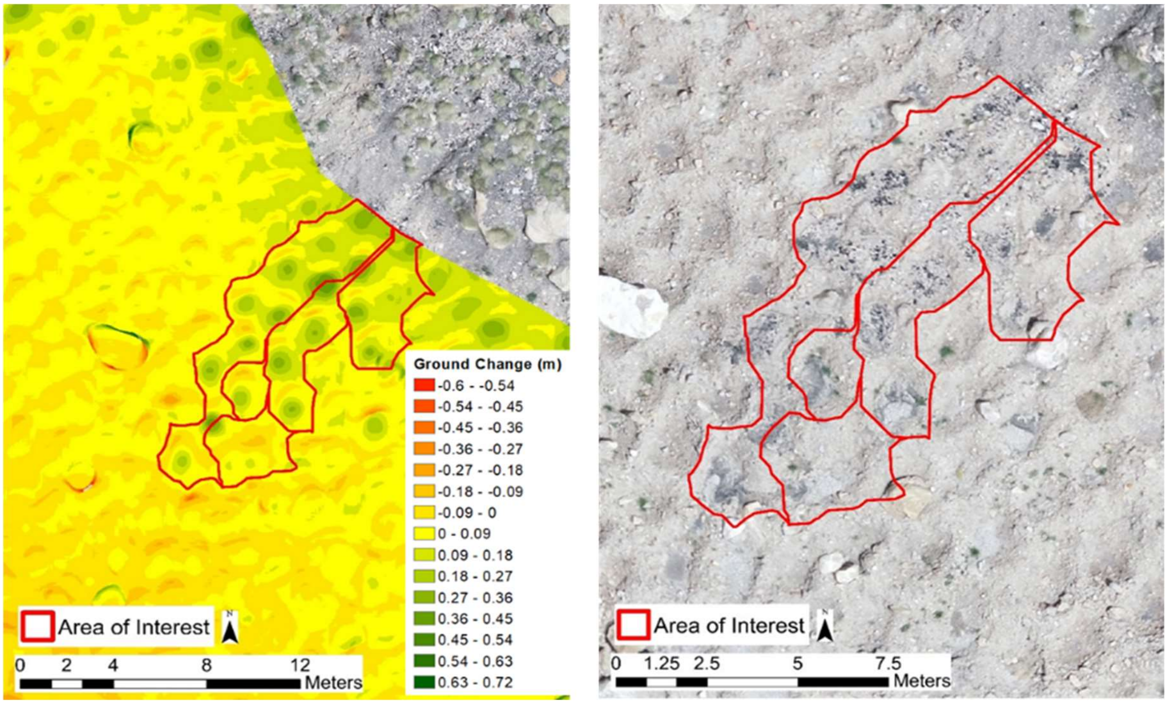

Figure 36. Pocks coalescing and elongating as they infill and erode.

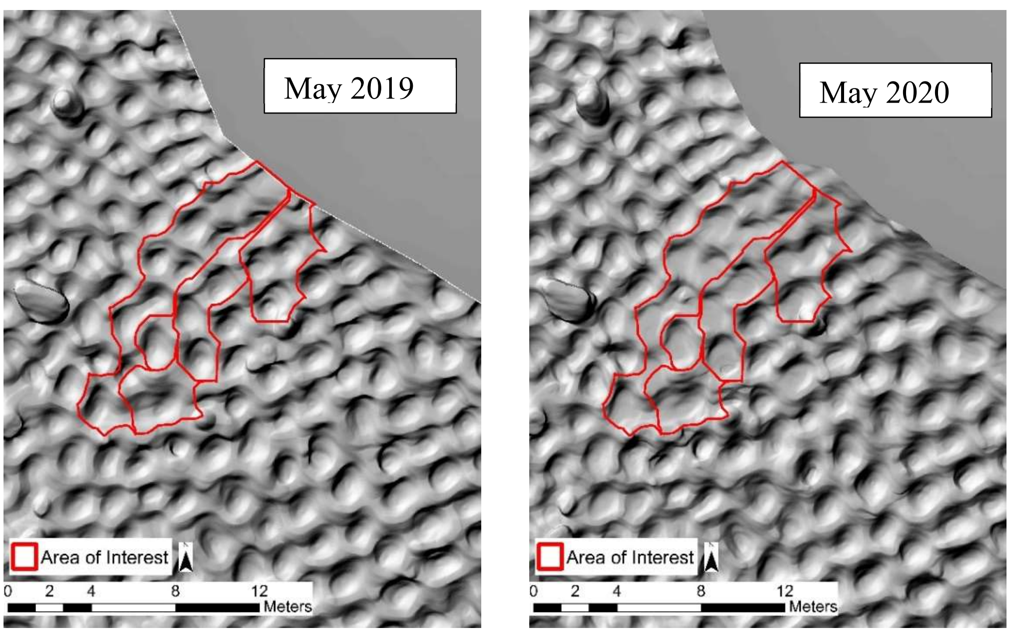

Figure 37. Shaded relief showing pocks filling over time at AOI #2 from 2019 to 2020.

Area of Interest #3 and #4

AOI #3 (Figure 38) is similar to AOI #2, but the cause of infilling is primarily due to increased vegetation cover within the pocks. Infilling (green areas) in this case is primarily due to dried Russian Thistle that has been blown into the pocks. Since the DSM is created using a photogrammetric process which does not penetrate through vegetation canopy, this increase represents a false positive. False positive elevation increases are also evident at AOI #4 (Figure 39). In this instance, the false positive is due to vegetation growing within each pock.

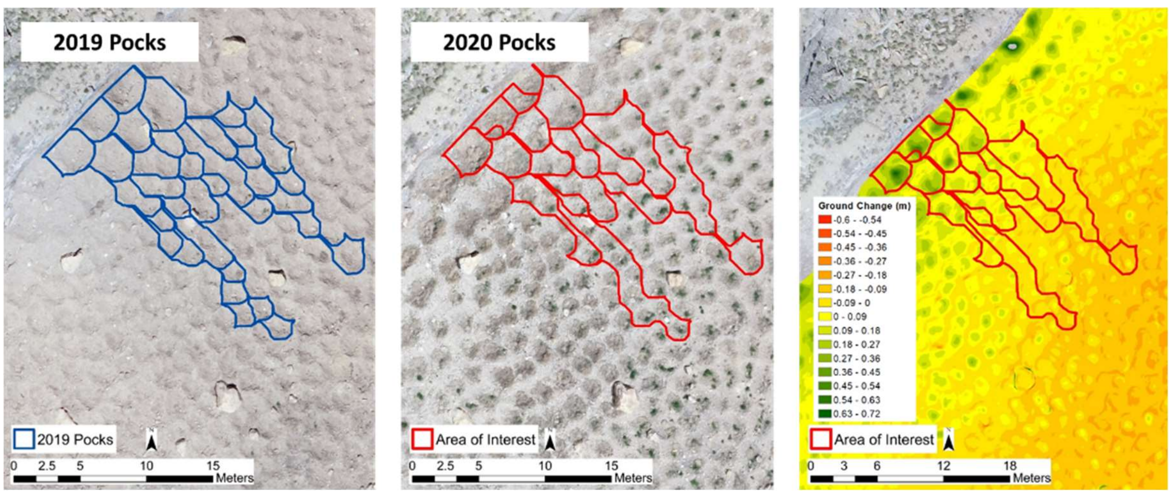

Figure 38. Vegetation giving a false signal in the change detection at AOI #4.

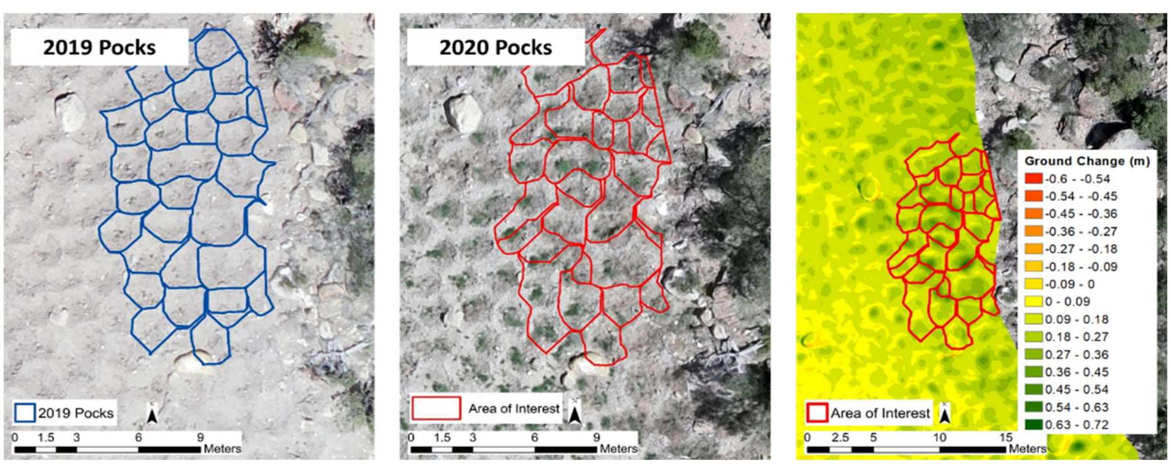

Figure 39. False signal from tumble weeds at AOI #3

Area of Interest #5

There are several areas at the site that significantly lowered in elevation between 2019 and 2020 by up to half a meter (Figure 40). These instances can be found primarily within 10 meters of the 5-foot-deep rock sediment trap running along the center of the canyon. We assume that this decrease in elevation is being caused by general surface settling. Figure 40 shows a general pattern of elevation decrease (assumed settling) as one moves closer to the drainage channel. We found, however, through ground observation and aerial imagery, that the pocks themselves are eroding in a similar fashion as the rest of the site, and vegetation is filling in.

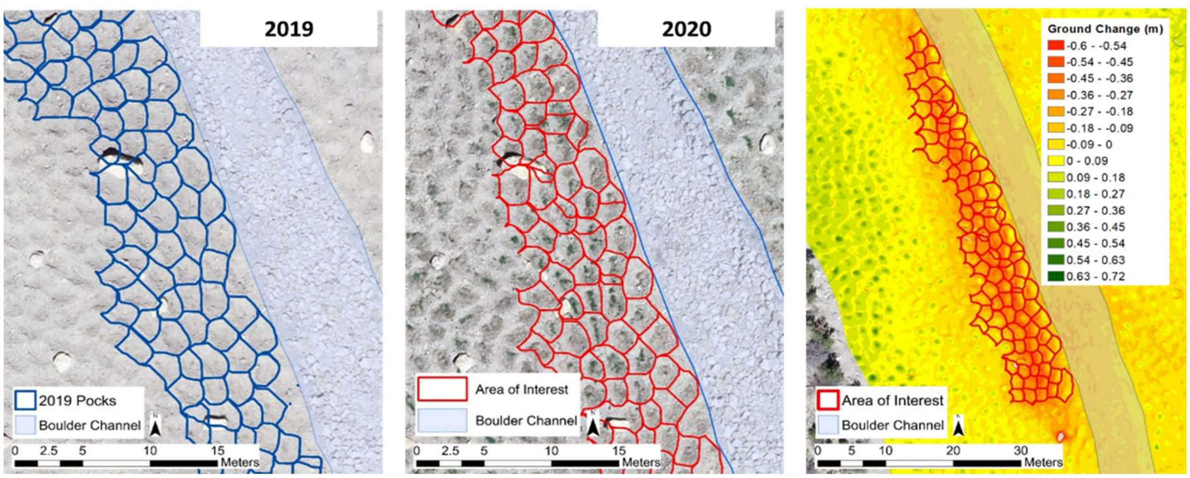

Figure 40. Area of extreme settling at AOI # 5

Area of Interest #6

The last area of interest (AOI #6) showed increased ground elevation, but no noticeable amounts of vegetation within pocks (Figure 41). This area occurred along the edge of the reclaimed area where we would expect increased sedimentation from the surrounding landscape.

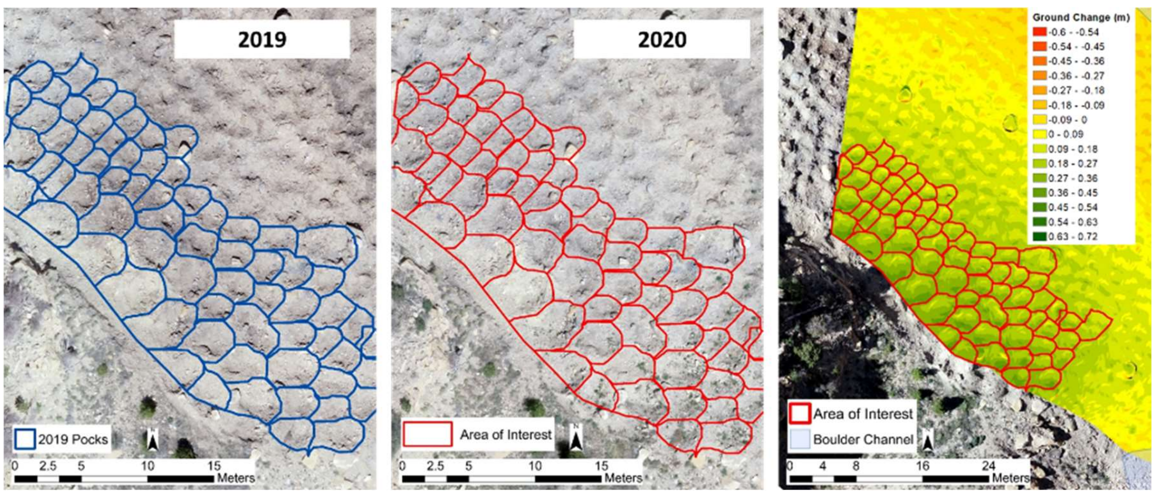

Figure 41. Area rising attributed to erosion from adjacent, unpocked landscape.

4.5. Vegetation (NDVI)

The NDVI derived from the Micasense imagery identified vegetation growing across both the Cottonwood and Des Bee Dove sites (Figures 42 and 43). The Cottonwood site showed vegetation growing at the bottom of each pock, while the Des Bee Dove site shows more vegetation growing across the original pocking structure. While the remnant pocking structure is visible in the imagery over Des Bee Dove, automated detection using the pocking tool was not possible due to the overgrowth of vegetation. The Des Bee Dove site, however, still shows vegetation distribution influenced by the distribution of pocks.

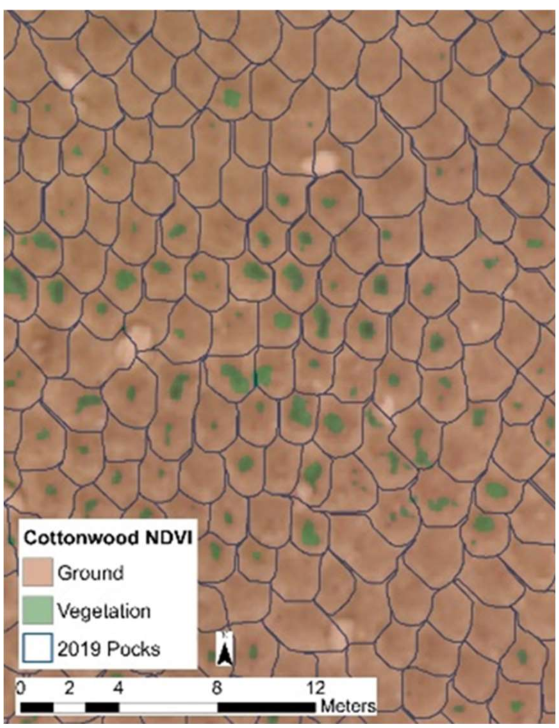

Figure 42. Vegetation growing within pocks at the Cottonwood site as identified by the NDVI.

Figure 43. Vegetation identified by the NDVI at the Des Bee Dove site.

4.6. Ground Evaluation: Erosion

All randomly sampled pocks showed evidence of infilling, with the side walls being the source of most sediment (Figure 44). However, we had difficulty getting accurate measurements using the shovel method to identify sedimentation layers due to variation in materials at the bottom of pocks ranging from soft soil to large rocks (Figure 45). This variation, along with minimal sedimentation across a 12-month time span reduced confidence in a quantitative measurement, though visual inspection showed evidence of erosion from pock walls and deposition in pock bottoms. We were not able to measure the same pocks across both years due to GPS location error.

Figure 44. Erosion along the pock walls can be seen in the central and far pocks.

Figure 45. Variation of the pock material across the site inhibited a consistent method to evaluate sedimentation at the bottom of the pocks.

Sediment staff points were measured both years for the same pock. However, GPS location errors forced us to manually locate and place readings into the correct pock locations by interpreting the 2.5cm imagery and images of the sediment staff pocks (Figure 46). This allowed us to compare staff measurements to the DSM difference map.

Figure 46. Example of using the ground images and aerial imagery to correlate locations and correct sediment staff GPS points, with red and blue circles corresponding to each other across the images.

While the random ground observation GPS points were not able to be corrected to individual pocks due to GPS error, the observations made while collecting them did allow for several larger events to be recorded. The site identified as AOI # 2 in the aerial imagery confirmed the ground change determination from the difference map with the pocks along the edge of the reclaimed area being completely full of sediment with adjacent downslope pocks infilling as well (Figure 47).

One erosion event recorded while sampling random pocks near AOI #5 was initially assumed to be an error in the digital surface model due to its large size (> 60 cm), but ground verification found it to be part of an extreme subsidence and erosion event (Figure 48).

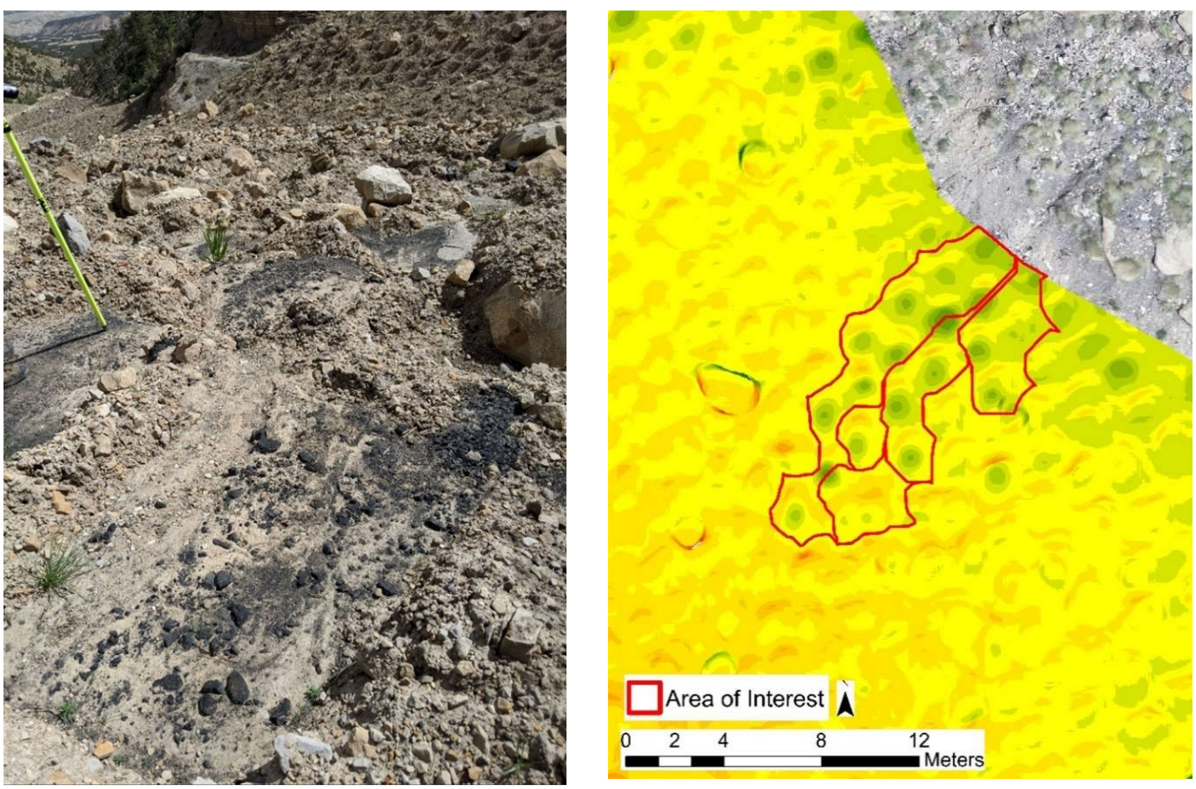

Figure 47. Ground verification of infilling pocks from AOI #2.

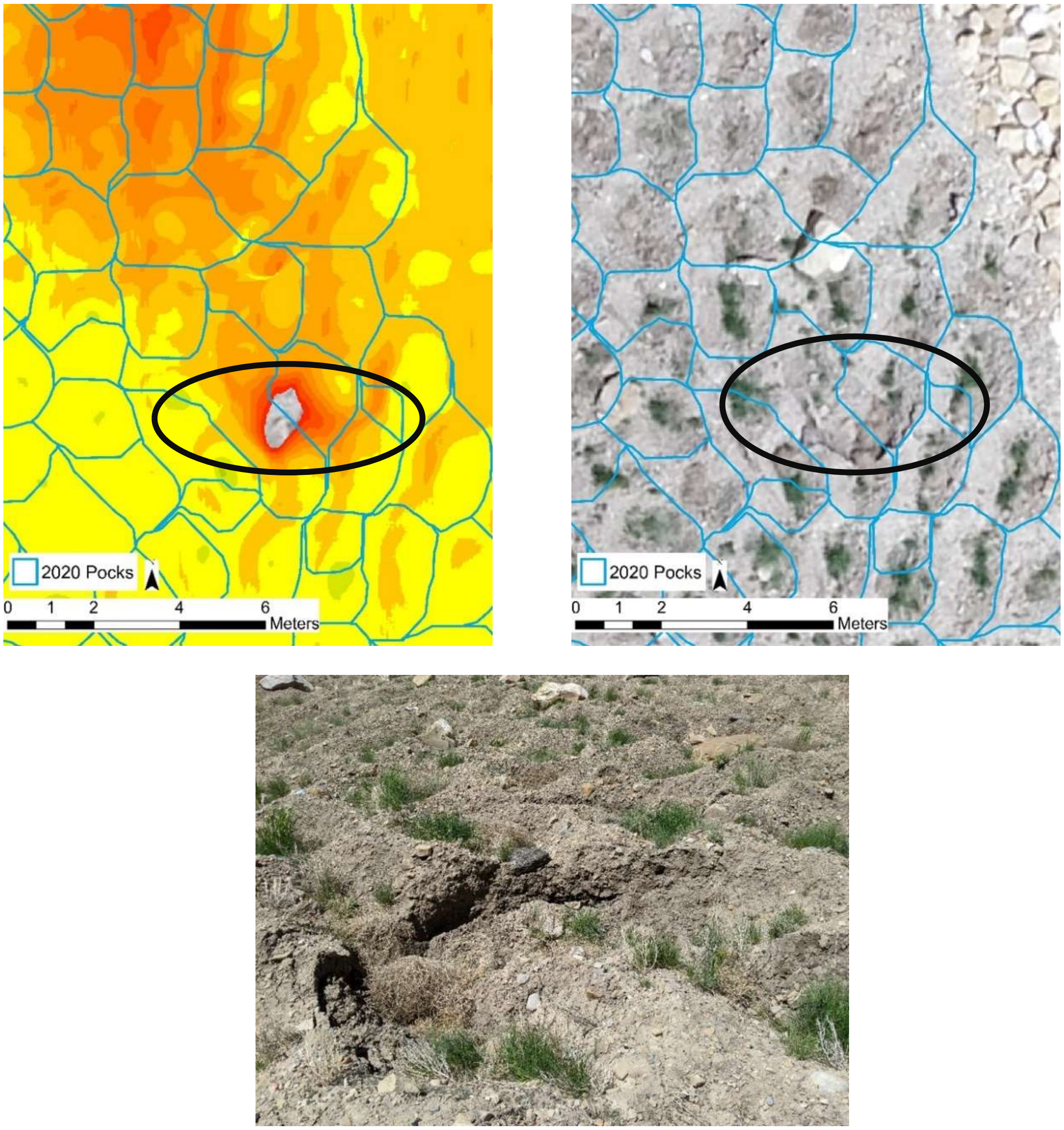

Figure 48. Top Left- The pock outlines overlaid on the DSM change map, showing an area assumed to be a DSM error. Top Right- Aerial imagery of location, showing a ridge formation at the same site. Bottom- The erosion/subsidence event verified on the ground.

4.7. Ground Evaluation: Vegetation

Field work conducted in 2019 found that 82% of the sampled pocks had actively growing vegetation. The 2020 field survey found that 100% of sampled pocks contained actively growing vegetation. Vegetation was growing generally at the bottoms of the pocks, but was also present along the ridges in many locations. Field-based estimates of vegetation canopy cover was not collected in either year. However, Figure 49 is representative of vegetation growth within and around pocks for both years.

Figure 49. Vegetation growing in separate pocks at Cottonwood in 2019 (Left) and 2020 (Right).

5. Discussion

Results from this work has shown that photogrammetric point clouds derived from UAS aerial imagery can be used to monitor infilling of pocked landscapes as well as vegetation growth. Analysis of control point Z values (elevation) estimated in 2019 and 2020 indicated an error rate of +/- 9 cm between the two years. However, this error rate may also be a function of the unexpected general subsidence of the terrain along the central portion of the pocked area as indicated by lower elevation values along this portion of the canyon in the summer 2020 imagery and visualized in Figure 33. We assume that the large boulders used for ground control also experienced a degree of subsidence. The continuation of monitoring activities in the Cottonwood study site should take this subsidence into account to better quantify error of the elevation difference estimate. Extending this technique to other landscapes should include the establishment of permanent control points that are relatively stable in their X, Y, and Z positions. This was a resource not available to us at the Cottonwood site forcing the use of large (semi) permanent boulders.

Another confounding factor in estimating pock infilling was the presence of vegetation within pocks. While vegetation growth within the pocks is the ultimate desired result of this reclamation method, its presence influences the digital surface models that reflect the vegetation canopy height rather than erosional infilling of pocks. A potential solution to this issue is to use airborne Lidar which would provide superior terrain models compared to the photogrammetric approach, but would also be more expensive due to equipment costs. Alternatively, if the photogrammetric method is used, more attention could be focused on erosion along the edges of pocks rather than the deposition at the bottom. This focus on pock ridge lines would potentially allow for more accurate detection of inter-pock erosion events by identifying the change in ridgelines as they evolve from individual pocks to combined elongated drainages. This would mitigate the issue of vegetation growth affecting the digital surface models, allowing for additional years of monitoring of erosion with UAS derived photogrammetry.

We also found that identifying and enumerating each pock as individual "objects" using the pock tool, we could better track the condition of individual pocks and also evaluate changes in shape and connectivity between adjoining pocks. This tool may prove to be a better diagnostic method to monitor pocks through time as adjacent pocks merge.

To further improve our understanding of the effectiveness of pocking, future work should incorporate spatial databases of soil characteristics (texture, depth, etc.) as well as compatible UAS surveys immediately following the completion of the pocking process. Monitoring for vegetation establishment and health could also benefit from mapping of species composition utilizing multispectral sensors attached to the UAS.

Another step to better understand a pocked landscape would be to identify pour points between adjacent pocks by analyzing the digital terrain models of pock ridgelines. This would allow managers to identify where to expect prematurely merging pocks that potentially lead to premature erosional processes that allow sediment to escape the reclamation area. Identifying what, if any, effect overall slope steepness has on pocking would also be of use since pocks on a steep hillslope could potentially have a higher risk of failure compared to pocks on a relatively flatter surface.

6. Conclusion

This work has demonstrated that unmanned aerial systems can be effective at evaluating the effectiveness of pocking as a reclamation tool. While a formal cost/benefit analysis was not conducted, the benefits of obtaining repeated high spatial resolution imagery and digital terrain models of a reclaimed landscape using consumer grade, off-the-shelf, UASs is significant. These systems provide a landscape-level, permanent record of ground conditions that can provide land managers with a defensible product that not only assesses reclamation success but provides important data to help improve reclamation techniques.

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