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Dual-camera, high-resolution aerial assessment of pipeline revegetation

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Abstract Energy-extraction results in significant disturbance to rangelands in Wyoming and other western US states. Although reclamation is required by law, US General Accounting Office reports from 1999 and 2005 are clear that affected government agencies have—over much of the past decade—had difficulty accomplishing mandated environmental monitoring of extraction-related disturbance. We evaluated two pipeline rights of way (ROW) using nested images (1- or 2- with 13- or 20-mm ground sample distance (GSD)) acquired during Very-Large Scale Aerial (VLSA) surveys. Aerial monitoring allowed for the collection of large numbers of geocoded samples, and for subsequent cover measurements using methods with demonstrated accuracy equal to that of conventional ground-based methods. Both pipelines had vegetative-cover deficiencies relative to their Plan of Development (POD) requirements. Using bare ground and ground-cover measurements from the higher-resolution imagery, we present a spatial representation of each pipeline ROW that allows quick identification of sections of the ROW that may need further reclamation action to meet POD standards. We also present aerial monitoring costs. We recommend VLSA pipeline surveys as a means for facilitating required environmental monitoring and for addressing the monitoring backlog that has developed with increased energy-extraction activity.

Keywords Aerial photography · Aerial monitoring costs · Environmental monitoring · Ground-cover measurements · Point sampling · Spatial data

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Introduction

Energy extraction is a prominent use of public lands in Wyoming and many western U.S. states. In 2006, oil and gas operations on US Bureau of Land Management (BLM) administered public lands and federal mineral estate in Wyoming produced 28.5 million barrels of oil and 525.4 trillion cubic feet of gas, generating $1 billion in federal oil and gas royalties (BLM 2007). Extraction and associated activities result in significant disturbance to the soil and vegetation of affected lands. Although interim reclamation is required in some instances and monitoring of disturbances and land use was mandated by the 1968 National Environmental Policy Act (NEPA) and other laws, there is evidence that manpower and conventional monitoring technology have been insufficient to allow effective ecological monitoring of disturbances (GAO 1999, 2005; Bisson 2007). In 1999, a US General Accounting Office (GAO) report noted that the Department of the Interior (DOI) has the challenge of "… striking a balance between its two basic mandates—accommodating the demands for greater use and more consumption of resources with the demands to protect and conserve resources for the benefit of future generations." The report observed that DOI agencies often cannot identify the environmental impacts of energy extraction; instead of fact-based decisions, subjective judgments are used in assessing how limited budgetary resources should be spent protecting and preserving environmental resources.

Between 1999 and 2004, drilling permits issued by the BLM more than tripled. A 2005 GAO report described BLM's ability to meet its environmental mitigation responsibilities as being substantially lessened as a result of increases in drilling-permit workloads. Oil and gas-related revegetation monitoring has followed conventional ground-based methods (Alberta Environment 2004; Interagency Technical Team (ITT) 1996; Vogel 1987), but these methods have a low data-yield-to-cost ratio relative to remote sensing methods (Um and Wright 1998). Satellite imagery is available from a variety of sources, but is often much more costly than aerial photography and maximum resolution at present is 60 cm ground sample distance (GSD) (Quickbird[1]), a resolution too low to monitor anything but gross changes in vegetative cover.

The need for cost-effective, statistically-adequate monitoring allowing unbiased measurements of key environmental indicators has motivated more than 40 years of research in high-resolution aerial monitoring. Aldrich et al. (1959) introduced the Hulcher 70 mm camera for monitoring natural resources. The Hulcher allowed shutter speeds of 1/2,000 s and was the preferred aerial camera for large-scale (1:600 to 1:10,000) natural-resource assessments for more than two decades. Booth (1974) introduced intermittent aerial sampling while using the Hulcher to obtain photographs at scales near 1:1,000 for evaluating soil erosion in Nevada rangelands. Abel and Stocking (1987) also used intermittent aerial sampling (scale = 1:2,500, 35 mm camera) from which they estimated sediment yield from Botswana rangelands. The equipment and methods for obtaining high-resolution aerial photography from fixed-wing aircraft remained more or less static from 1959 until Booth and Cox (2006) used a Sport airplane (FAA 2004) and a modified Hulcher 70 mm film camera to acquire aerial photography with minimal motion blur at scales near 1:200, with subsequent resolutions of 1-mm GSD using a digital camera equipped with an image-stabilized telephoto lens (Booth and Cox 2008).

Advances in digital photography have overcome many of film's shortcomings and allow high-resolution aerial imaging to be a viable, economical monitoring tool for pipeline-reclamation and other natural-resource monitoring. Development of methods for acquiring and analyzing digital aerial imagery with resolutions comparable to what can be obtained on the ground offers the potential for substantial increases in monitoring efficacy, the creation of a permanent record of conditions at a specified time and place, and reductions in costs (Booth et al. 2005a, b, 2006a, b, c; Luscier et al. 2006). Here we assessed reclamation success relative to right-of-way (ROW) permitting requirements to evaluate the utility of reclamation monitoring using very-large scale aerial (VLSA) imagery (1 to 20-mm ground sample distance (GSD)).

Methods

Image acquisition

VLSA surveys are designed to systematically sample an area of interest by acquiring numerous images at regular intervals over the survey area (Booth and Cox 2006). VLSA is a sampling tool, not a mapping tool. We used

[1]Throughout this paper the mention of trade names or commercial products is for information only and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

an externally-mounted dual-camera equipment module consisting of two digital SLR cameras (1Ds 11.1 megapixel with a 100 mm, *f*/2.8 lens; 1DsMarkII 16.7 megapixel with an 840 mm, image stabilized, *f*/5.6 lens; Canon USA, Lake Success, NY) set for 1/4,000 s shutter speed, a Trackair navigation system (Trackair, Oldenzaal, Netherlands), an LD90-3100VHS-FLP laser rangefinder used as an altimeter (Riegl, Orlando, FL), a 401036 light meter (Extech, Waltham, MA) and a GPS16 WAAS-enabled GPS receiver (Garmin, Olathe, KS). During the first year of the study (2006), three laptop computers (Dell, Round Rock, TX) were on board the aircraft to run the navigation system and collect images sent over firewire from the cameras. The following year (2007) images were all saved to 16 GB compact flash cards (SanDisk, Milpitas, CA), so only one laptop was required on board to handle navigation. A 10-cm LCD screen located near the pilot provided a graphic display of the flightlines and targets, as planned using ArcGIS 9.0 (ESRI, Redlands, CA). The cameras were automatically fired by the navigation system and images and location data were captured concurrently. Altitude above ground level (AGL) and light intensity values were collected by a custom logger that simultaneously displayed the information for the pilot on the LCD monitor (Robert Berryman Consulting, Boulder, CO). Because of its capability for safe, slow flight (65–95 kph), we used a Moyes–Bailey Dragonfly powered by a Rotax 4-stroke, 115-horsepower turbocharged engine. The two-seat aircraft has a 10.5-m wing span and a US Federal Aviation Agency "Sport Airplane" designation (FAA 2004). Images were saved as RAW files on both cameras, later converted to Tagged Image File Format (TIFF) images using Canon Digital Photo Professional 2.0. Both cameras were time-synchronized with the laptop prior to every flight, such that all images and metadata could be linked precisely by time. We used Merge software (Robert Berryman Consulting) to match images with GPS coordinates, altitude AGL, light intensity and ground speed, the latter two being predictors of image quality. We then used ArcGIS 9.0 (ESRI) to derive slope, aspect and elevation for each image location.

Study sites

The Lost Creek pipeline

The Lost Creek pipeline is a 61-cm natural gas header that runs 193 km across the Red Desert in southern Wyoming (Fig. 1), mostly on public land administered by the BLM, Lander and Rawlins Field Offices. The pipeline was laid and the 25-m wide ROW reseeded with 17 kg/ha native grass/shrub seed mix in 2000. This study focused specifically on a 32-km ROW segment crossing the Arapahoe Use Area in the Green Mt Common Allotment, south of Jeffrey City, WY (42°14′ N, 107°54′ W). Most of the ROW falls inside the 25–30 cm precipitation zone dominated by Wyoming big sagebrush (Asteraceae *Artemisia tridentata* Nutt. var. *wyomingensis* (Beetle and A.L. Young) S.L. Welsh), with elevation of 2,020–2,190 m and average slope of 2.3°. An aerial survey along the ROW was completed in June 2006, by acquiring 258 pairs of images from an average AGL of 150 m using the dual-camera VLSA

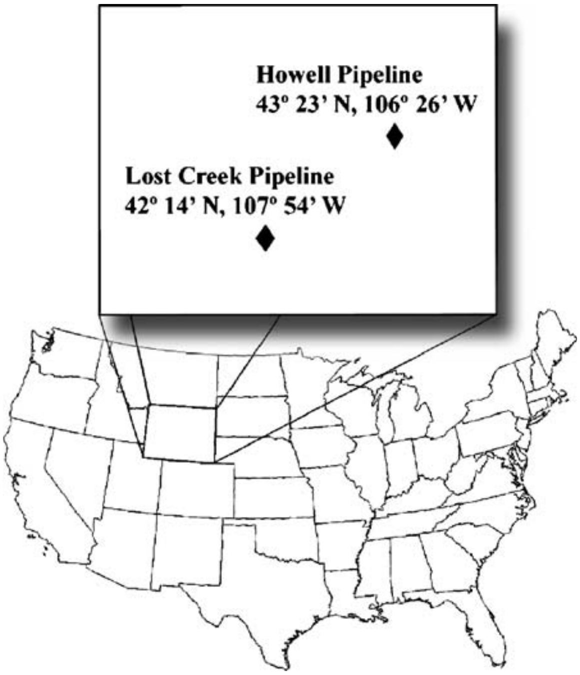


Fig. 1 Location of study sites relative to the rest of Wyoming and the US

system. Each image pair consisted of one 13-mm GSD image (36 × 54-m field of view (FOV)), and a nested 1.3-mm GSD image (4 × 6-m FOV). Distances between aerial sample locations along the Lost Creek pipeline ranged between 54 and 917 m with an average separation of 140 m (±76 SD). The survey was part of a larger aerial survey of the area, and some images from the larger survey were used as part of this study. Ferry distance from landing strip to pipeline was ~30 km.

The Howell pipeline

The Howell pipeline is a 41-cm CO_2 trunkline that runs 188 km across central Wyoming, mostly on public land administered by the Bureau of Land Management Casper Field Office. The pipeline was laid in 2003 and the 25-m wide ROW reseeded with 15 kg/ha native grass/shrub seed mix in late 2004. This study focused specifically on a 35-km ROW segment crossing the Salt Creek watershed, north of Casper, WY (43°23′ N, 106°26′ W). Most of the ROW falls inside the 30–36 cm precipitation zone dominated by Wyoming Big sagebrush, with elevation of 1,450–1,700 m and average slope of 3.2°. An aerial survey along the ROW was completed in June 2007, by acquiring 152 pairs of images from an average AGL of 240 m using the dual-camera VLSA system. This survey was flown at 240-m AGL, rather than the 150-m AGL altitude of the Lost Creek pipeline survey, to increase the FOV of the images so that more lower-resolution images would span the full width of the disturbed area. Each image pair consisted of one 21-mm GSD image (57 × 86-m FOV), and one 2.1-mm GSD image (7 × 10-m FOV). Sample separation distance ranged from 90 to 1,500 m and averaged 293 m (±175 SD).The survey was part of a larger aerial survey of the area, and some images from the larger survey were used as part of this study. Ferry distance from landing strip to pipeline was ~50 km.

Image analysis

For both pipelines, reclamation success is defined in submitted Plans of Development (POD) by (1) vegetative cover of at least 75% of adjacent land, (2) species composition to include a high percentage of seeded species with natural invasion, (3) the ability to withstand established grazing, (4) the reproduction of reseeded plants is evident, (5) planted woody species have >50% survival, (6) noxious weeds are controlled and (7) vegetative cover mitigates visual impacts (Lost Creek Gathering Company 2000; Howell Petroleum Corporation 2003). No time limit exists to meet reclamation goals.

We assessed reclamation success by measuring vegetation cover by life form using SamplePoint, a manual photo-interpretation software program that facilitates point classification of imagery and has a demonstrated ground-cover measurement accuracy of >90% using 1-mm GSD imagery (Booth et al. 2006b). (Comparison measurements of bare ground from 1 and 2-mm GSD imagery suggest measurements from the latter will be within ~85% of those from the 1-mm GSD imagery (unpublished data).) For each image, 100 points arranged in a systematic grid were classified into one of the following life form and ground-cover categories: INgrass, INforb, INshrub, INlitter, INsoil, INrock, INunknown, OUTgrass, OUTforb, OUTshrub, OUTlitter, OUTsoil, OUTrock and OUTunknown, where IN refers to the area inside the ROW and OUT refers to undisturbed areas adjacent to ROW. Wide field of view images (36 × 54 m) covered both the ROW and adjacent areas, but were discarded if less than 25 sample points fell in either of these areas. Vegetation cover within and adjacent to the ROW were thus simultaneously measured from each image. Small field of view images (4 × 6 and 7 × 10 m) typically covered either the ROW or adjacent area, but rarely both. Thus, the small FOV images were divided into two groups, such that vegetation cover was measured within and adjacent to the ROW from separate image sets, which were also thinned where less than 25 sample points fell within the intended sampling area. Since most small FOV images taken over the ROW hit only the ROW, additional images from the larger aerial survey that were adjacent to, but within 300 m of, the ROW, were used for comparison. In images taken over the ROW that also included areas outside the ROW, classification points falling outside the

ROW were not utilized in ROW cover means (i.e., OUT points were not counted), and vice versa.

Since every large FOV image used for analysis contained both IN and OUT ROW portions, paired T-tests were used to compare every cover class. Since small FOV images from IN and OUT of the ROW were not aligned, standard T-tests were used to compare cover means for the Howell pipeline. Welch's T-tests were used for the Lost Creek pipeline IN and OUT comparisons because F-tests showed differences in sample variance for most cover categories. Where the F-test was not significant, use of Welch's T-test did not change the reported P-value, so we used Welch's for consistency. All statistical results were generated using Excel 2003 (Microsoft, Redmond, WA) and Prism 3.0 (Graph Pad Software, San Diego, CA). Comparing vegetative cover inside to outside the ROW is a measure of reclamation success defined by indicator 1 of the PODs. Measurements of vegetation cover also addressed indicators 3–7 since adequate cover is a measure of the revegetation survival—and over the long term, of reproduction—in the face of grazing and other environmental stressors. Each image was examined for weedy species (indicator 6) and if detected, the cover measured. The ease with which the ROW can be distinguished from adjacent land addresses visual impacts (indicator 7).

Evaluation of the utility of VLSA monitoring for pipeline ROW monitoring

We compared cover measurements made from the two image resolutions used for each pipeline to each other (within pipelines) to determine whether the measurements for that pipeline would give the same result. Since sample sizes were unequal between small and large FOV data sets for both study sites (Table 1), Welch's T-tests, which do not assume equal sample variance, were used for comparisons. Costs for the aerial assessment were tabulated and are reported.

Results and discussion

Image analysis

Lost Creek pipeline

Measured from the small FOV imagery, shrub and forb cover were lower inside the Lost Creek pipeline right-of-way (ROW) relative to the undisturbed, adjacent land ($P < 0.001$), while grass and litter cover were higher ($P < 0.001$, Table 1). Total vegetation cover was 22% inside the ROW compared to 40% outside, or 55% of the adjacent undisturbed land. Bare ground was 57% within

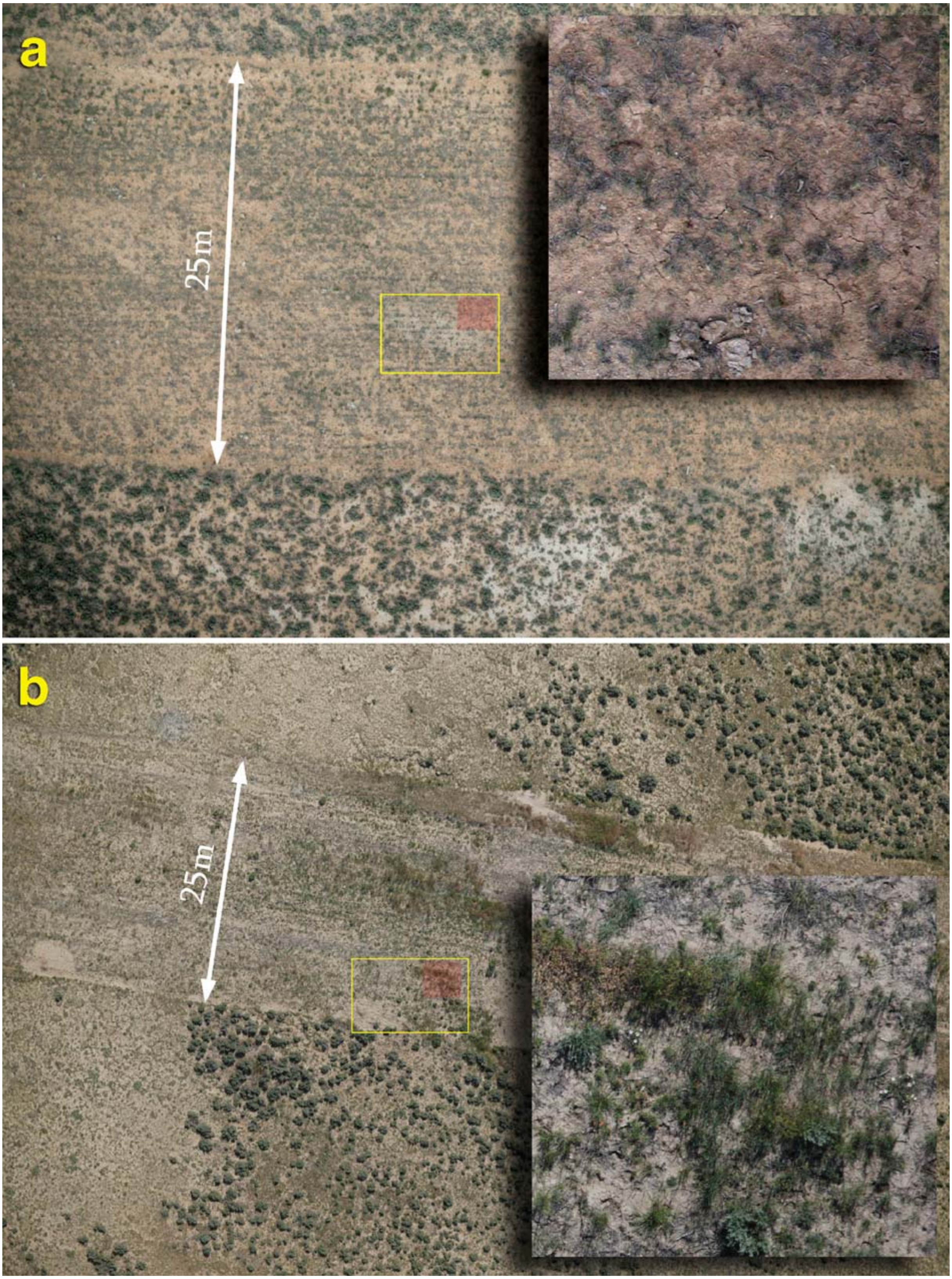
Table 1 SamplePoint vegetation cover measurement means±standard deviation inside and adjacent to (within 300 m) the Lost Creek pipeline ROW, from both small FOV imagery (4 × 6 m, 1.3-mm GSD) and large FOV imagery (36 × 54 m, 13-mm GSD)

	Small FOV		T-test IN vs OUT[a]	Large FOV (n= 219)		T-test IN vs OUT	T-test FOV comparison IN[a]	T-test FOV comparison OUT[a]
	Inside ROW ($n = 213$)	Outside ROW ($n = 85$)		Inside ROW	Outside ROW			
Grass	17.3 ± 14.2	7.8 ± 10.2	< 0.001	12.6 ± 13.9	4.9 ± 10.9	< 0.001	< 0.001	0.03
Forb	2.4 ± 4.6	5.0 ± 4.9	< 0.001	0.2 ± 1.2	0.3 ± 3.5	0.17	< 0.001	< 0.0001
Shrub	1.8 ± 4.6	26.8 ± 11.7	< 0.001	2.8 ± 3.8	40.0 ± 14.3	< 0.001	0.01	< 0.0001
Litter	21.2 ± 9.8	16.7 ± 7.5	< 0.001	24.5 ± 11.2	14.4 ± 6.2	< 0.001	0.001	0.01
BG	56.5 ± 17.4	37.9 ± 13.3	< 0.001	59.5 ± 17.7	36.3 ± 14.0	< 0.001	0.08	0.4
Rock	0.9 ± 1.9	2.2 ± 6.3	0.07	0.7 ± 1.4	4.2 ± 6.2	< 0.001	0.2	0.01

P-values are given for cover comparisons between areas inside and adjacent to the ROW for each image set. Paired T-tests were used to compare cover values from the large FOV image set. P-values are also given for comparisons of cover measured from small and large FOV images, both inside and outside the ROW

BG bare ground

[a] Welch's correction was used due to unequal sample variance


a
25m
b
25m

the ROW—1.5 times that of the adjacent reference area (Table 1). The low vegetative cover (7 years from seeding) raises the question of whether the new plant community is sufficiently resistant to grazing, drought and other environmental stresses and whether it is reproducing at sustainable levels. Clearly, visual impacts are still present (Fig. 2). Weeds were not detected in the images or by on-the-ground surveys (John Likens, BLM, Lander; personal communication, October 2007) suggesting that weeds are not currently a threat to successful reclamation although the large amount of bare ground relative to the undisturbed vegetation suggests the ROW is at risk for invasion by weedy species.

Howell pipeline

Total vegetation cover (grass, forb and shrub), as measured from the small FOV imagery, was 38% inside, and 51% adjacent to, the ROW ($P <$ 0.05, Table 2), giving the Howell pipeline ROW an overall mean vegetation cover that is 74% of the undisturbed adjacent land after three growing seasons. A later assessment may be needed to determine if reproduction of reseeded plants is adequate. Visual impacts are present (Fig. 2), and will likely remain until shrubs mature. Weeds were not detected in the images, suggesting that they are not currently a threat. Shrub establishment on the Howell pipeline ROW, at 74% of the undisturbed adjacent cover, has been much more successful than on the Lost Creek ROW, at only 7%.

Measuring reclamation success

Several sections of the Lost Creek ROW have low bare ground (Fig. 3). We examined slope, aspect, vegetation community and proximity to drainages as possible factors influencing low bare ground, but determined that none of these factors were common to all points in the sections. Nevertheless, the ability to ask and answer such questions is important and data displays like Fig. 3 are useful because they allow land managers to readily assess land conditions at specific locations. Single values, like the mean for vegetation cover along the whole extent of a ROW, are an inadequate measure of reclamation success, and can be misleading since much of a pipeline ROW may fail to meet plan of development (POD) requirements. On a sample by sample basis, only 14% of the *sampled area* in the Lost Creek pipeline ROW, and only 28% of the *sampled area* in the Howell pipeline ROW have bare ground values equal to or less than values for the adjacent land. Similarly, only 20% of the Lost Creek sampled area, and only 40% of the Howell sampled area has total vegetation cover equal to or greater than 75% of the vegetation cover of the adjacent land. Sample images are a permanent record of conditions at a specific time and place. When compared with succeeding assessments, they allow for a robust determination of vegetation trend and on-the-ground success or the lack thereof.

The importance of image resolution and the utility of VLSA imagery for spatial monitoring of ROW revegetation

Point sampling is based on the assumption that a point is infinitely small—without area (Cook and Stubbendieck 1986, page 59)—and we have previously discussed the importance of image resolution in obtaining accurate ground-cover measurements from images (Booth et al. 2005b, 2006b). Regardless of this theoretical basis, we are often asked if 1-mm GSD imagery is necessary for accurate ground-cover measurements. If 1-mm GSD imagery is not needed, then we would expect no differences between paired ground-cover measurements from 1- and 2-mm (small FOV) versus 13- and 20-mm GSD (large FOV) imagery. For the Lost Creek pipeline, bare ground values from small and large FOV images were not different, for both inside and outside the ROW ($P >$ 0.05). Rock cover values from both large and small FOV images from inside the ROW also were not different ($P = 0.2$), although rock values from

◀ **Fig. 2** VLSA survey images from **a** Lost Creek pipeline ROW and **b** Howell pipeline ROW. Both panels show the full view from the wide FOV image, the outline of the nested small FOV image (*yellow*) and an enlarged portion of the small FOV image (*red*)

Table 2 SamplePoint vegetation cover measurement means±standard deviation inside and adjacent to (within 300 m) the Howell pipeline ROW, from both small FOV imagery (7 × 10 m, 2.1-mm GSD) and large FOV imagery (57 × 86 m, 21-mm GSD)

	Small FOV (n= 67)		T-test IN vs OUT	Large FOV (n= 131)		T-test IN vs OUT	T-test FOV comparison IN[a]	T-test FOV comparison OUT[a]
	Inside ROW	Outside ROW		Inside ROW	Outside ROW			
Grass	17.7 ± 20.6	21.0 ± 18.2	0.3	43.0 ± 26.1	28.7 ± 17.4	< 0.001	< 0.001	0.005
Forb	8.04 ± 8.59	13.9 ± 10.3	< 0.001	1.4 ± 3.2	2.7 ± 4.7	< 0.01	< 0.001	< 0.001
Shrub	12.1 ± 12.2	16.4 ± 12.0	0.04	10.0 ± 10.1	25.1 ± 12.7	< 0.001	0.2	< 0.001
Litter	8.9 ± 8.2	6.4 ± 6.2	0.04	2.4 ± 4.2	2.9 ± 4.7	0.2		< 0.001
BG	53.1 ± 23.8	40.9 ± 24.9	0.004	43.2 ± 21.8	40.0 ± 20.3	0.05	0.005	0.8
Rock	0.2 ± 0.5	0.2 ± 0.6	0.79	0.1 ± 0.4	0.4 ± 0.9	< 0.001	0.2	0.06

P-values are given for cover comparisons between areas inside and adjacent to the ROW for each image set. Paired T-tests were used to compare cover values from the large FOV image set. P-values are also given for comparisons of cover measured from small and large FOV images, both inside and outside the ROW

BG bare ground

[a]Welch's correction was used due to unequal sample variance

both image resolutions outside the ROW were different ($P = 0.01$). All other cover classes—that is all vegetation classes—were different between small versus large FOV images, both inside and outside the ROW ($P < 0.03$, Table 1).

For the Howell pipeline, bare ground was not different between large and small FOV images outside the ROW ($P > 0.05$, Table 2), but *was* different between large and small FOV images inside the ROW by about 10% ($P < 0.01$, Table 2). Rock cover means were not different between resolutions, either inside or outside the ROW ($P > 0.05$). Shrub cover measurements were not different between image resolutions inside the ROW ($P = 0.2$), but were different by 9% outside the ROW ($P < 0.01$). All other cover classes were different between small versus large FOV images, both inside and outside the ROW ($P < 0.01$).

Taken together, the data show that there can be significant disagreement between measurements made from large FOV images (13 and 21-mm GSD) and small FOV images (1 and 2-mm GSD). Cover differences between the two image resolutions were not consistent for any cover class, and do not seem subject to a standard offset prediction. For example, grass measurements from large FOV compared to small FOV differed by +25,+8, −3 and −5. Such variance hinders accurate compensation for inherent errors in cover measurements made from lower resolution imagery. Given the significant differences in measurement outcomes between the two FOVs, we reject the null hypothesis and recommend the use of small FOV, high resolution imagery (1 and 2-mm GSD) for measuring vegetative cover. But, we emphasize the value of the large FOV, lower resolution imagery (13 and 21-mm GSD) in measuring such things as disturbance width and area, occurrence of invasive species, and for providing an overview of the area to help put small FOV images into context with their surroundings, or to determine whether the small FOV image falls inside the ROW.

Satellite images, small-scale aerial imagery and videography, while useful to some extent for monitoring, cannot provide the high resolution required to identify species (including weeds) or allow accurate ground cover measurements. However, this shortcoming must be balanced against the inability of VLSA imagery to acquire an uninterrupted image of the ROW, such as is available with satellite and most small-scale imagery. Data needs will determine the appropriate monitoring tool. To assure valid statistical comparison of small FOV images IN and OUT of the ROW, we recommend aerial acquisition directly over the ROW, and a second acquisition flight targeted for 30 m adjacent to the ROW. We found no partic-

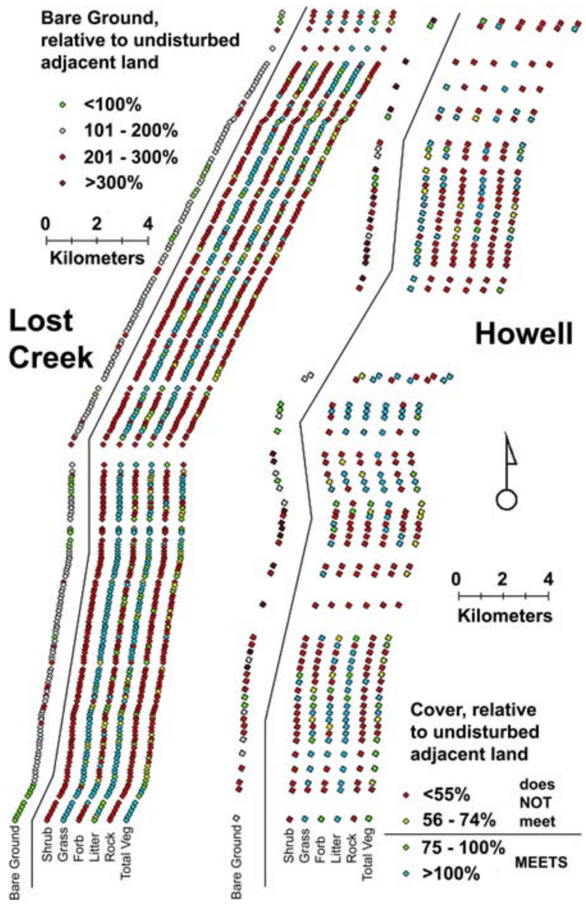


Fig. 3 Cover values for bare ground, shrub, grass, forb, litter, rock and total vegetation (shrub, forb and grass) as a percentage of adjacent, undisturbed land cover values, measured from small field of view (~5 × 8 m) aerial images and plotted to scale, provide a quick and comprehensive view of reclamation progress along two ~35 km stretches of pipeline rights of way in central Wyoming. Cover breaks indicate areas that meet or do not meet the vegetative cover requirements established by the Plans of Development. Skips in the Howell pipeline sequence are the result of technical problems encountered during that survey

ular advantage to acquiring more images that included the full width of the Howell pipeline ROW and recommend the lower flight altitude for future surveys.

Costs

Although the total in Table 3 suggests a survey cost of \$67 to \$73/km of pipeline, these surveys

Table 3 Costs of monitoring each pipeline ROW using VLSA imagery

Task	Time (h)	Cost/h (\$)	Cost (\$)
Flight planning	4	40	160
Flight time	1	150	150
Pilot ground time	2	50	100
Technician support	3	40	120
Data compilation	3	40	120
Image analysis	100	12	1,200
Data analysis	12	40	480
Total for each ROW			2,330

were conducted as part of larger projects. There are additional costs associated with the larger projects that might inflate the cost/km. Mobilization costs include time spent preparing the airplane for trailering, and re-assembly at the job site. Travel costs include time spent en route, lodging, and per diem [14 h mobilization + 12 h travel = 26 h at $90/h (pilot+ground support) = $2.340; lodging and per diem = $200/day)]. A $6,000 annual start up cost for insurance results in a $1,000 charge to each major project during the field season. If completed as stand-alone projects, the total cost for each pipeline survey, including image analysis and data summary, would have been about $5,700. It is also important to note that weather delays (high wind, precipitation etc.) will increase costs. On the other hand, the pipeline segments surveyed in this study were both ~35 km portions of pipelines totaling hundreds of kilometers in length. Surveying longer portions of pipelines would spread the mobilization and travel costs out, reducing the cost per kilometer.

Conclusions

The demand for energy resources has put unprecedented pressure on public land management agencies and on the surface resources they manage. This pressure has highlighted the inadequacy of conventional ground-based ecological monitoring for identifying revegetation insufficiencies of pipeline ROWs. Because conventional methods have a low data-yield-to-cost ratio, they are not practical for obtaining the high sample numbers and the sample distribution needed to fully represent and describe the condition of ROW surface resources. If problems in ROW revegetation are not identified, they will not be rectified. The work reported here has demonstrated that VLSA surveys provide representative knowledge through systematic, sufficient, and affordable sampling along the length of the ROW disturbance. Intensive VLSA sampling documented that 7 years from seeding <1/4 of the Lost Creek pipeline ROW meets POD requirements. This finding should raise an alarm with the responsible companies and land managers. Similarly, the Howell pipeline, 3 years from seeding, has less than 50% of the disturbed ROW in an agreed-to condition.

We conclude that the lower resolution imagery acquired for the Howell pipeline (2 vs 1, and 20 vs 13 mm GSD) provided no benefit and we recommend acquisition of the higher resolutions as was acquired for the Lost Creek pipeline. We also recommend a survey flight line be directly over the ROW with a second flight line targeted for ~30 m adjacent to the ROW.

Using VLSA surveys to conduct multi-resolution sampling along pipeline ROWs is recommended for obtaining the large sample numbers and accurate ground-cover measurements needed to accomplish actionable environmental monitoring. The image-based data sets created by the surveys are a permanent record, and provide spatial evidence identifying unmitigated environmental problems for each pipeline segment, thus allowing fact-based decisions by responsible companies and agencies for allocating budget to protecting or rehabilitating affected ROW surface resources.

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