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The effect of spatial resolution on measurement of vegetation cover in three Mojave Desert shrub communities

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Abstract

Moderate resolution remotely sensed imagery (20–30 m) has lacked sufficient spatial resolution to accurately measure total vegetative cover in arid environments because the density of plant cover is generally too low to significantly influence spectral reflectance. New and emerging imagery is now available at significantly higher spatial resolutions, resulting in pixel sizes equal to or smaller than many dominant desert shrubs. This had led to an opposing problem, where desert shrubs now exhibit multi-modal probability functions associated with the individual elements of the plant, such as foliage, woody stems and branches, and shadows within and around shrub canopies. High resolution imagery was collected at three spatial resolutions for study sites in the south-central Mojave Desert of California to (1) determine the effect of spatial resolution on the detection of four common species of shrubs (*Chilopsis linearis*, *Psorothamnus spinosus*, *Larrea tridentata*, and *Ambrosia dumosa*), (2) assess the affect of increasing pixel size on the accuracy of area estimates of shrub cover, and (3) assess the accuracy of vegetation cover measurements when compared to vegetation cover measured in the field. Spatial resolution greater than 1.0 m was not capable of discerning a large percentage of the shrubs in this region of the Mojave Desert. Yet, high correlation ($r^2 = 0.71-0.93$) was found between field measurements of percent cover and those derived from imagery at spatial resolutions ranging from 0.6 to 1.0 m. The results indicated that a spatial resolution of 1.0 m or smaller was necessary to

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estimate percent cover and the area of individual shrubs from high-resolution imagery. Spatial resolution is dependent on the abundance and size of species of desert shrubs within plant communities, however 1.0 m resolution was found to be adequate for this region of the Mojave Desert.

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1. Introduction

Public lands in the Mojave Desert have seen a loss of vegetation cover caused by rapid population growth, off-highway recreational use, historical overgrazing by livestock, and training on vast military installations (Fleischner, 1994; Hunt et al., 2003). Remote sensing has been used to inventory and monitor vegetation cover in this arid environment at the landscape level using satellite imagery (Frank 1984; Driscoll et al., 1997). However, when vegetation cover is sparse and vascular plants are widely scattered, cover generally has been under estimated because of the mixed composition of materials within large pixels, such as Landsat Thematic Mapper (LTM). Vegetation, soil and litter combine to affect the composite spectral response within these pixels, making it difficult to extract the vegetative component from the spectral reflectance (Smith et al., 1990; Pickup et al., 1993; Borel and Gerstl, 1994; Puyou-Lascassies et al., 1994; Bateson and Curtiss, 1996; Ray and Murray, 1996; Shoshany et al., 1996; Sohn and McCoy, 1997; Tanser and Palmer, 1999).

Now that new and emerging systems have become available with a range of very high spatial resolutions, it may be possible to accurately map the amount of dominant vegetation cover, and potentially map the size and distribution of individual species of shrubs. However, shrub canopies consist of the woody and leafy components of the plant, as well as the open spaces in the canopy. Therefore, the spectral response from desert shrub canopies exhibit multimodal probability density functions in very high resolution imagery. Spectral reflectance can vary from high reflectance from shrub foliage in the near-infrared wavelength, to low near-infrared reflectance from gaps in the canopy that consist of a matrix of woody branches and stems, and underlying litter and exposed soils. Red wavelength reflectance can vary from low reflectance from foliage when leaves are present, to higher reflectance from woody branches, to lower reflectance in the shadows of the interior and perimeter of the shrub canopies. As such, it is necessary to determine the optimal spatial resolutions to measure shrub cover in dominant vegetation communities in the Mojave Desert with very high spatial resolution imagery (Woodcock and Strahler, 1987; Wang et al., 2001).

The three objectives of this study were to determine the effect of spatial resolution on the detection of four common species of shrubs (*Chilopsis linearis*, *Psorothamnus spinosus*, *Larrea tridentata*, and *Ambrosia dumosa*) in three different study sites in the south-central Mojave Desert, to assess the affect of increasing pixel size on the accuracy of area estimates of shrub cover, and to assess the accuracy of vegetation cover measurements when compared to vegetation cover measured in the field.

2. Materials and methods

2.1. Study sites

Three study sites were selected because they represent dominant plant communities that commonly occur in disturbed areas throughout the Mojave Desert (Fig. 1). This area is part of the Great Basin Section of the Basin and Range physiographic province (Hunt, 1967). Principal landforms consist of mountain ranges, alluvial fans, ephemeral streams, playas, and lava flows. Vegetation is sparse, consisting mainly of shrubs and non-native grasses. Two study sites, Wood Canyon and Sand Hill, were located on the Marine Corps Air Ground Combat Center (MCAGCC) at Twentynine Palms, California. This landscape, like other arid military installations, is susceptible to long-term disturbance caused by both anthropogenic and physical factors because vegetative growth and recovery are slow. The third study site, Gold Crown Wash, was located at a desert wash managed by the Bureau of Land Management, approximately 32 km southeast of Twentynine Palms, where disturbance was caused primarily by off-highway vehicles.

Wood Canyon (Fig. 2), an evergreen subdesert shrubland, was a highly disturbed desert wash. It was a primary traffic corridor for military vehicles. Continuous disturbance allowed this site to remain relatively stable, with low vegetation cover and diversity, and widely scattered shrubs that have a large range in size. *C. linearis* primarily occupied dry washes, intermittent streams and other water courses. Wood Canyon was unique because relatively small shrubs were absent as a result of being destroyed by large vehicles. Co-dominant shrubs, *C. linearis* and *P. spinosus*, were more abundant because vehicles avoided these larger plants. These large deciduous shrubs may grow between 3–9 m tall, and have open, spreading crowns. Foliage was present on both species during the study.

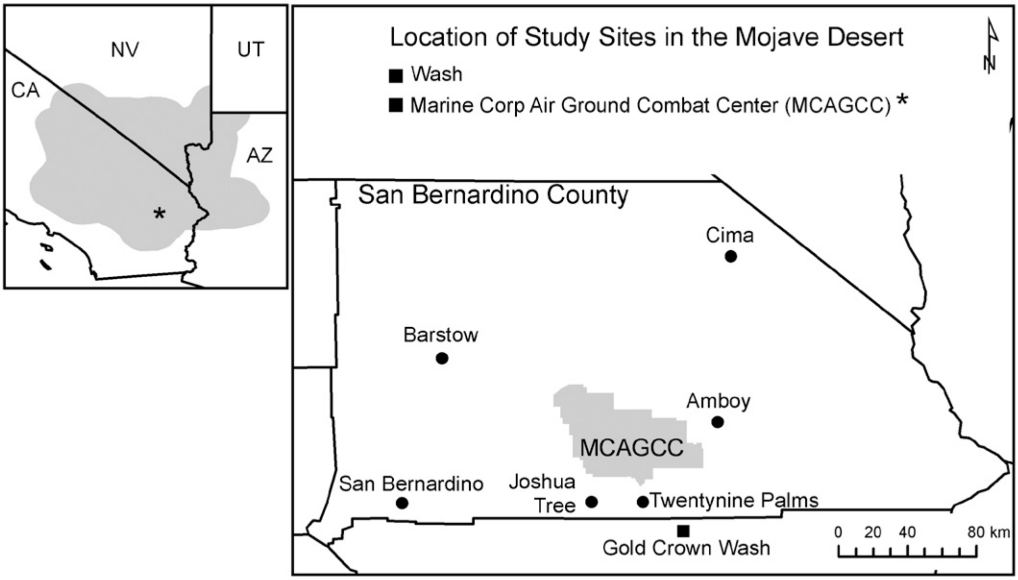

Fig. 1. Location of study sites in the Mojave Desert.

Fig. 2. Wood Canyon is a disturbed desert wash that is a primary traffic corridor for military vehicles at the Marine Corp Air Ground Combat Center.

Fig. 3. Sand Hill is a relatively flat region dominated by *Larrea tridentata* and *Ambrosia dumosa*, where shrub cover and abundance is greater where off-highway traffic is prohibited (shown) and less abundant where military training occurs nearby.

Sand Hill (Fig. 3), a deciduous subdesert shrubland, was a relatively flat region dominated by *L. tridentata* and *A. dumosa*. *L. tridentata* was ubiquitous throughout the Mojave Desert, being one of the most abundant and oldest shrubs in the desert (Barbour, 1969). This shrub grows to an average height of 1.5–2 m. The canopy was generally open,

Fig. 4. Gold Crown Wash exhibits off-highway vehicle use surrounded by relatively large *Larrea tridentata* and *Psorathamnus spinosus*, with other shrubs that occur less frequently, particularly *Atriplex polycarpa* and *Ambrosia dumosa*.

which allowed the underlying soils to be visible from above. *A. dumosa* was found on mesas and plains, commonly interspersed with *L. tridentata*; it was compact and dense with an average height of 0.7 m. Relatively few other species were observed at Sand Hill. This site was divided by an unpaved road; to the north the area was used by military vehicles during training exercises, while to the south off-highway traffic has been prohibited since the 1980s to protect water supplies and desert tortoise (*Gopherus agassizii*) habitat. Shrubs in both areas were compact, dense, and relatively small in comparison to other populations in the Mojave Desert.

Gold Crown Wash (Fig. 4), an evergreen subdesert shrubland, consists of two co-dominant species, *L. tridentata* and *P. spinosus*. Other shrubs, particularly *Atriplex polycarpa* and *A. dumosa*, occurred less frequently. The site was a long and broad desert wash that exhibited evidence of localized off-highway vehicle use. *P. spinosus* ranged in height from 2–10 m. *P. spinosus* are confined to desert washes due to their high water requirements. This site offered a contrast to the other two study sites, both in terms of land use and associated impacts (military versus recreational use), with greater diversity and variability in the size of desert shrubs.

2.2. Remote sensing image acquisition

A computerized airborne multi-camera imaging system (CAMIS) was mounted on a fixed wing aircraft and flown over the three study sites (Fig. 5). The aircraft was flown at altitudes ranging from 1020 to 3820 m altitude to collect multiple resolution imagery (0.6, 1.0, 2.0 m) where the higher resolution images were nested within the larger spatial resolution images (Table 1). Flight lines were marked with 2 m × 4 m white panels spaced

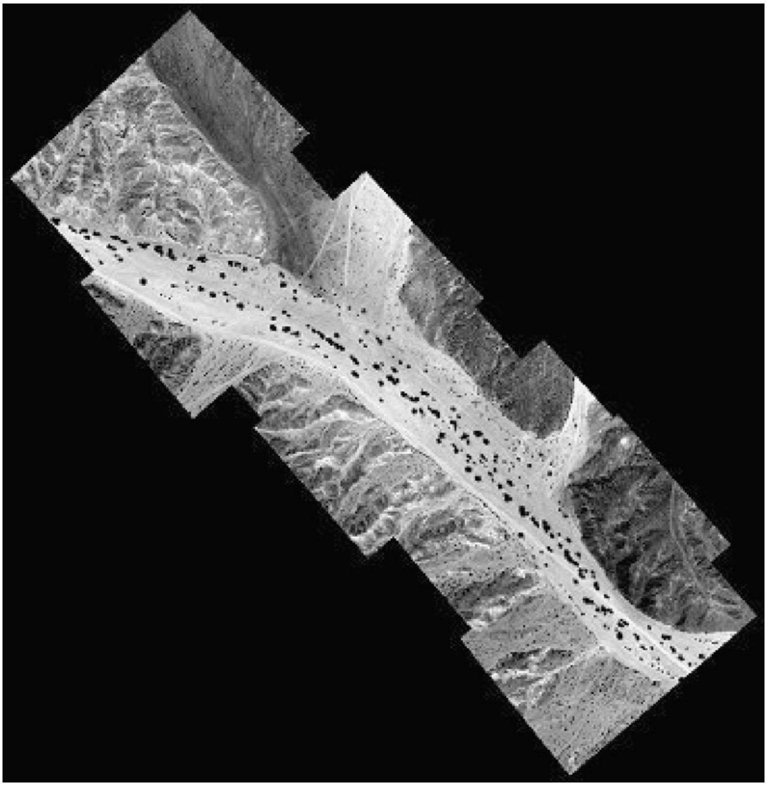

Fig. 5. Computerized airborne multi-camera imaging system mosaic of Wood Canyon study site showing 1.0 m spatial resolution.

Table 1
Attributes of imagery collected with computerized airborne multi-camera imaging system in the Mojave Desert

Spectral band	Band centers (nm)	Spatial resolution at altitude		
		1020 m	2000 m	3820 m
Band 1 blue	450	0.6 m	1.0 m	2.0 m
Band 2 green	550			
Band 3 red	650			
Band 4 near-infrared	800			

at the beginning, middle, and end of each flight line. CAMIS images were corrected for vignetting using band-to-band registration Cosine[4] bi-directional reflectance. The panels were used to assess whether additional radiometric calibration was necessary between the nested resolutions; however, all image resolutions were collected at each study site within approximately 30 min of flight time, resulting in nominal atmospheric or radiometric differences. Images were used in the analysis without the need for further radiometric corrections.

2.3. Image classification

Vegetation cover was derived from each spatial resolution using a K-means iterative clustering algorithm based on the ISODATA algorithm (Swain, 1978). Clustering was used because the spectral response of desert shrub canopies exhibited multi-modal probability density functions in very high resolution images. Shrubs that have a multimodal spectral characteristic must be decomposed into these uni-modal subclasses. Using post-classification sorting, uni-modal subclasses were combined to depict the actual shape of the shrubs. Clustering was performed using all four spectral bands, with a maximum of 25 uni-modal spectral classes. This was determined to be a sufficient number of spectral classes to differentiate between the leafy and woody components of the shrub canopy and the underlying litter and bare ground. The clusters that represented the uni-modal spectral characteristics of the shrub canopy (foliage and woody stems and branches) were aggregated together as a shrub. All other clusters were aggregated as bare ground. Pixels that were considered to be part of the shrub were processed with a clumping algorithm that assigned each contiguous group of shrub pixels into a unique feature class to represent an individual shrub. The area of each individual shrub was then available for each of the three spatial resolutions. The maps of shrub cover derived from each spatial resolution were used to assess the percentage of shrubs that could be detected in each spatial resolution, the effect of increasing pixel size on the measurement of shrub area, and the accuracy of shrub cover when compared to cover measurements derived from field transects.

2.4. Field measurements of community cover and Shrub area

Traditionally, when field measurements are collected for the purpose of validating information extracted from remotely sensed imagery, the transect size and shape are determined with respect to the spatial resolution of the sensor and are generally larger than the size of an individual pixel. For example, 50–100 m line intercept transects have been used to characterize the percent cover within large plant communities when working with moderate resolution imagery, such as LTM (30 m). Random azimuth transects about a center point also have been used to characterize the area enclosed by areas of fixed radius. The radius can be large when working with moderate resolution imagery, or small when working with very high resolution imagery. The advantage of small fixed radius transects is that complete enumeration of plants can be made within the radius. Thirty fixed radius transects of 2.5 m radius each were randomly selected at each of the three study sites. The area of each field transect was 33 pixels at 0.6 m, 19 pixels at 1.0 m, and 10 pixels at 2.0 m. The geographic coordinate of the center point of each transect was recorded with a real-time differential global positioning system (GPS). Measurement of total vegetative cover was recorded within each transect as near as coincident with image acquisition as possible. In addition, 158 individual shrubs were selected in the three study sites to characterize the size and variability of shrubs in this region of the Mojave Desert. Each shrub was located in the imagery using the geographic coordinate collected in the field with the GPS. These shrubs were used to determine what spatial resolution was necessary to discern the occurrence of these species of shrubs.

2.5. Regression analysis

The percent of the area of each transect that was classified as vegetation with imagery was regressed with the field measurements of total vegetation cover to assess accuracy of vegetation estimates derived from imagery in these Mojave Desert communities.

Linear regression was used to determine if a significant difference existed between the area measurements of desert shrubs when measured with different spatial resolutions (Eq. (1)). Controls were established for interactions of species, resolution, and study sites.

$$Y_{i,j,k,l} = \mu + \mathrm{Sp}_I + R\mathrm{Sp}_{i,j} + Si_k + \mathrm{Sp}Si_{i,k} + I_{i,k,j} + I_{i,k,j} + E_{i,j,k,l}, \tag{1}$$

where $Y_{i,j,k,l}$ is the response variable, in area derived by field measurements; Sp_i is the fixed effect of the ith species (area derived from imagery); $\mathrm{RSp}_{i,j}$ is the interactive effect of ith species and jth resolution; Si_k is the random effect of kth site, normally distributed with 0 mean and σ_1^2 variance; $\mathrm{Sp}Si_{i,k}$ is the random interaction of study site and species, $\sim N(0, \sigma_2^2)$; $I_{i,k,j}$ is random interaction of shrub number, study site and species, $\sim N(0, \sigma_3^2)$; $E_{i,j,k,l}$ is the random error, $\sim N(0, \sigma^2)$.

3. Results

3.1. The effect of spatial resolution on the detection of four shrub species

Each of the 158 shrubs was located in the imagery using the geographic coordinate collected in the field with the GPS. Images were evaluated by study site, where there would be a variety of shrubs of different species, and by species aggregated from all study sites (Table 2). The percentage of shrubs that could be discerned decreased as the pixel size increased at all three study sites. Sand Hill, where the size of *L. tridentata* varied considerably, and *A. dumosa* were small relative to the other shrubs, resulted in low identification rates for all three spatial resolutions at 0.6 m (62.5%), 1.0 m (40.6%), and 2.0 m (11.9%). Gold Crown Wash was dominated by two larger species of shrubs, *P. spinosus* and *L. tridentata*, where identification rates of 74.1% (0.6 m), 65.6% (1.0 m), and 50.0% (2.0 m) were achieved. Wood Canyon had the largest species of shrub, *C. linearis*, which resulted in higher rates of identification at 0.6 m (85.0%) and 1.0 m

Table 2
Percent of shrubs identified in multiple spatial resolution imagery

	Study sites[a]			Dominant species[b]			
	Sand Hill	Gold Crown	Wood Canyon	*Ambrosia dumosa*	*Psorothamnus spinosus*	*Chilopsis linearis*	*Larrea tridentata*
N	64	58	40	34	26	34	64
Resolution							
0.6 m	62.5	74.1	85.0	32.4	65.4	82.4	95.3
1.0 m	40.6	65.6	77.5	17.7	46.2	82.4	76.6
2.0 m	11.9	50.0	47.5	5.9	35.6	47.1	40.6

[a] All species combined together at each study site.

[b] Individual species examined together at all study sites. *N* = sample size.

(77.5%), yet still less than half at 2.0 m (47.5%). These results suggest that 0.6 m spatial resolution would be necessary to inventory these desert shrubs when all species are aggregated together at study sites.

3.2. The effect of spatial resolution on the measurement of shrub area

The area of the 158 shrubs was measured in each of the spatial resolutions to determine the effect of increasing pixel size on the measurement of the area of individual species. This was important because the clumping of individual pixels into shrub features resulted in different area measurements for the same shrub, depending on the spatial resolution of the image. In general, the shrub features become larger as pixel size increased, leading to overestimation of shrub area with larger pixels.

The average size of each species of shrub was calculated for each resolution (Table 3). The average size of shrubs for all four species increased as pixel size increased. Maps of shrub cover derived from imagery at 0.6 m (2567 ha), 1.0 m (7733 ha), and 2.0 m (8152 ha) also illustrated that overestimation of the area of shrubs occurred as spatial resolution increased. Comparison of shrub cover from these three resolutions indicated which measurements were statistically different (Table 4).

No significant difference existed between the area measurements for *A. dumosa* and *P. spinosus* with 0.6, 1.0 or 2.0 m imagery. Therefore, 2.0 m imagery would be just as effective as the higher resolution imagery for estimating shrub area of these two species.

Table 3
Effect of image spatial resolution on shrub species area (m^2)

Resolution	*Ambrosia dumosa*			*Psorothamnus spinosus*			*Chilopsis linearis*			*Larrea tridentata*		
	N	Mean	S.D.	*N*	Mean	S.D.	*N*	Mean	S.D.	*N*	Mean	S.D.
0.6 m	11	1.51	0.72	18	12.10	8.83	28	37.90	43.05	61	9.81	7.95
1.0 m	6	2.00	2.00	14	10.40	9.87	28	34.00	39.69	47	11.20	9.64
2.0 m	2	3.00	1.41	10	16.00	13.55	17	60.50	70.59	26	18.60	13.38

N = sample size, S.D. = standard deviation.

Table 4
Pair-wise comparison of area measurements derived from multiple spatial resolution imagery for four dominant species of plants in the Mojave Desert

Spatial resolution	*p* values							
	0.6 m				1.0 m			
	S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4
1.0 m	0.57	0.19	0.73	0.22				
2.0 m	0.06	0.00	0.00	0.90	0.15	0.00	0.00	0.24

A *p*-value <0.05 indicated a significant difference in the area measurements when derived from different resolutions. S_1 = *Ambrosia dumosa*, S_2 = *Chilopsis linearis*, S_3 = *Larrea tridentata*, S_4 = *Psorathamnus spinosus*.

Table 5
Relationship between image cover estimates and field transect measurements for dominant plant communities at three study sites in the Mojave Desert

Study sites	Spatial resolution (m)	r^2	a_0	a_1
Wood Canyon	0.6	0.89	−3.38	0.82
	1.0	0.81	11.70	0.76
	2.0	0.74	1.96	0.63
Sand Hill	0.6	0.51	3.05	0.98
	1.0	0.75	9.24	1.53
	2.0	NA[a]	NA	NA
Gold Crown	0.6	0.85	0.09	0.92
	1.0	0.74	5.06	0.84
	2.0	0.71	5.04	0.73

[a] NA = not available due to instrument error during image collection.

The results for *C. linearis* and *L. tridentata* both indicated that 0.6 and 1.0 m imagery were not significantly different, but that 1.0 m imagery was significantly different from 2.0 m. This indicated that 1.0 m spatial resolution would be optimal to measure the area of both of these species.

3.3. The effect of spatial resolution on the accuracy of vegetation cover estimates

The accuracy of shrub area measurements derived from the multiple spatial resolutions was determined by linear regression with measurements of shrub cover derived from the field transects (Table 5). Wood Canyon resulted in high r^2 values for all three spatial resolutions ($r^2 = 0.89-0.74$). This site had the most abundant vegetation cover and the largest shrubs. Gold Crown wash also resulted in very high r^2 values for all three spatial resolutions ($r^2 = 0.85-0.71$). This site had a wider range in the size of the shrubs and greater species diversity. Sand Hill, however, provided mixed results ($r^2 = 0.51-0.75$). This site had relatively small *L. tridentata* and very small *A. dumosa*. These overall results indicated that the multiple spatial resolutions provided relatively accurate shrub cover measurements with high spatial resolution imagery.

4. Discussion and conclusions

The objective of this study was to determine the effect of spatial resolution on the detection and measurement of four common species of shrubs in the Mojave Desert. The results indicated that relatively high r^2 were observed between field measurements of percent cover and those derived from imagery at spatial resolutions ranging from 0.6 to 2.0 m. However, the area of individual shrubs derived from high spatial resolution imagery varied by species. As pixel size increased beyond 1.0 m, less than 50% of the individual shrubs sampled in the field could be identified in the imagery. The number of shrubs that could be identified for each study site was proportional to the relative size of the dominant shrub at each site.

Spatial resolution has a statistically significant influence on the measurement of the area of each species. The effects of spatial resolution were more pronounced for smaller shrubs (*A. dumosa* and *L. tridentata*) and shrubs that tend to be isolated with open canopies (*C. linearis* and *P. spinosus*). Most agreement between the area of the shrubs in the nested resolutions came from the 0.6 and 1.0 m imagery. The area of individual shrubs was over-estimated as pixel size increased to 2.0 m. This resulted because a single pixel could represent an individual shrub and bare ground, but the spectral contribution of the shrub would dominate the pixel. As a result the entire pixel was classified as a shrub. If this pixel was adjacent to another shrub pixel then these two pixels were clumped to form an even larger shrub feature, when in fact, there may have been two separate shrubs on the ground. As a result, the area of shrubs increased as pixel size increased. Shrub cover derived from imagery at 0.6 m (2567 ha), 1.0 m (7733 ha), and 2.0 m (8152 ha) illustrated that large differences in cover occurred depending on the spatial resolution of the imagery.

At some larger pixel size, bare ground should dominate the spectral response of a pixel and individual shrubs would not be discerned. The largest pixel size used in this study was 2.0 m, therefore, we could not determine what size pixel would then begin to underestimate shrub area, as happens with moderate resolution sensors such as LTM.

The results indicated that 0.6–1.0 m spatial resolution was necessary to accurately estimate the area of shrubs from imagery. Historically, an airborne platform would have to be used to acquire imagery at this spatial resolution. These resolutions are now available from satellite platforms, thereby providing access to repetitive coverage of disturbed desert lands. The use of high-resolution satellite imagery would enable land managers to systematically monitor changes in vegetation cover over time. Managers could measure the impact of disturbance or improvements in land condition and evaluate and monitor land rehabilitation efforts. However, higher spatial resolution imagery will be needed to provide area estimates of individual species of shrubs. The required resolution will depend on the size of the dominant or co-dominant species within communities.

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