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Mapping saguaro cacti using digital aerial imagery in Saguaro National Park

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Abstract. Population research on the saguaro cactus (*Carnegiea gigantea*) has historically been limited to repeat monitoring efforts in small plots with areas of 1 to 4 hectares. Large extent saguaro censuses of areas $>2.59 \text{ km}^2$ have not been undertaken. This research developed an automated shadow detection method for mapping mature saguaros in digital aerial imagery using saguaro shadows as proxies for saguaro locations. The shadow method detected 446,092 saguaro shadows in aerial imagery of 231 km^2 of the Saguaro National Park (SNP) near Tucson, Arizona. The results were validated against saguaro location data in 11 small plots provided by SNP staff. The shadow method correctly identified 58% of mature saguaros in these 11 plots. Twenty-one percent of the saguaros in the plots did not produce a shadow signature in the imagery. Fieldwork was conducted in two plot locations to investigate reasons why these mature saguaros failed to produce shadow signatures in the aerial imagery, which showed that vegetation interference, rocky slopes, and shadow alignments were the primary factors that precluded shadow signatures from appearing in the imagery. This research provides a methodology for automated large-area saguaro mapping, which will be useful in long-term population monitoring and saguaro ecology research. © 2018 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JRS.12.036016](https://doi.org/10.1117/1.JRS.12.036016)]

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1 Introduction

Natural resource managers, residents, tourists, and researchers consider the saguaro cactus (*Carnegiea gigantea*) to be a valuable natural and cultural resource worthy of scientific inquiry and preservation. The esthetics of a desert landscape dominated by towering multiarm cacti are unique to the Sonoran Desert as the saguaros range is primarily limited to southwest Arizona and northern Sonora, Mexico. The saguaro's values as a cultural symbol¹ and as an ecological key-stone species² are well documented. Desire to protect and preserve the saguaro was first codified in the establishment of Saguaro National Monument in 1933 to protect a remarkable stand of saguaros east of Tucson known at the "cactus forest." A second district to the west of Tucson was added in 1961 to protect the land and saguaros from mining interests.³ Observations of saguaro mortality in the early 1940s catalyzed an era of research into saguaro ecology, disease, growth, and distribution that continues to the present day.³

This research seeks to add to the existing body of saguaro monitoring research by developing a methodology to map saguaros on larger extents than any past effort. Mapping saguaros using shadows in aerial imagery has the advantage of being much less time and labor intensive than *in situ* surveys. Large extent censuses can be undertaken with a minimum investment using automated detection. A large census reveals spatial patterns that would not be detectable in small plots. This could point researchers to areas of relatively high or low saguaro density, which would yield insight into the variables that affect saguaro population dynamics. Large censuses

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undertaken years apart could produce population change data that would be useful for pinpointing areas of growth or decline for further study.

A one square mile area (259 hectares) in the northwest corner of Rincon Mountain District (RMD) known as “Section 17” (Fig. 1) was surveyed by Gill and Lightle⁴ in 1941 and again by Conner et al.⁵ in 2011 to 2012. These efforts represent a truly impressive amount of organization and labor and the largest extent saguaro studies that have been performed to date. Because of the effort and expense involved, large extent field survey censuses, such as these, are unlikely to be regularly repeated. While these one square mile (259 hectares) census efforts represent the largest saguaro census efforts in terms of area, the areas studied still comprise <1% of the total area of Saguaro National Park (SNP) and are not representing the range of saguaro density distributions across the park.

Although shadows are often treated as unwanted noise in remote sensing research, they can be useful in object identification and feature measurement. Comber et al.⁶ presented a method for measuring the heights of buildings in satellite imagery by analyzing neighboring areas of high reflectance contrast. Shettigara and Sumerling⁷ employed tree heights and shadows as calibration data to estimate building heights based on building shadows. Our research used a somewhat similar approach of using a ratio of shadow and nonshadow regions to score pixels based on the likelihood of being within a saguaro shadow. The shadow method differs from Comber et al.⁶ and Shettigara and Sumerling⁷ in that this research attempted to detect feature presence but not to estimate feature height. In addition, the aerial imagery used in this research contains a range of acquisition dates and times, while Comber et al.⁶ and Shettigara and Sumerling⁷ used singular satellite imagery scenes. Although the measurement objectives are unique to each research effort, shadows have been shown to be reliable proxies for object detection and height measurement.

Satellite-based approaches are unlikely to be effective for saguaros due to their small signature from nadir view and lack of significant phenological change. However, fine spatial resolution pan-chromatic Worldview-3 satellite imagery provides a spatial resolution of 32 cm, which may be sufficient for reliable saguaro mapping. This imagery is currently being used in a saguaro mapping pilot effort by the Earth Resources Observation and Science Center. However, the research presented here utilized the Pima Association of Governments (PAG) aerial imagery of SNP because it is the finest spatial resolution (15.24 cm) imagery currently available and, therefore, presents the best opportunity for reliable remote sensing of saguaros.

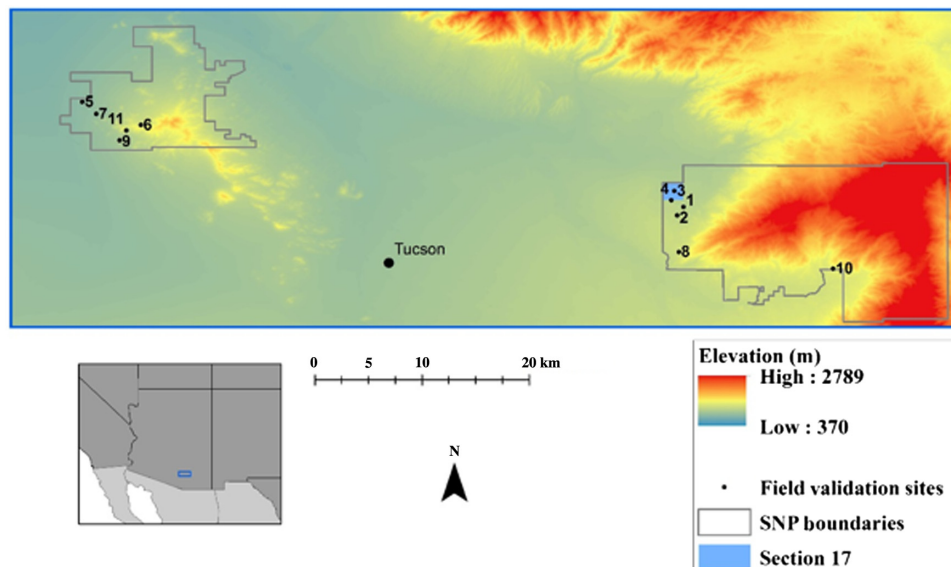


Fig. 1 Digital elevation model, SNP districts, and 11 2010 field survey locations. We conducted fieldwork at sites 6 and 8 to investigate saguaros that were missing from the aerial imagery. The TMD is shown to the northwest of Tucson. The RMD is shown to the east of Tucson. A large proportion of this district lies above the maximum saguaro elevation threshold of 1550 m.

2 Study Area

This research focused on saguaro detection within the boundaries of SNP. The park is divided into two districts: Tucson Mountain District (TMD), located to the northwest of the city of Tucson, and RMD, located adjacent to Tucson on the east side (Fig. 1). Most of the lower elevation areas in the park are classified as Sonoran desertscrub, including Arizona Upland and Plains of Sonora subdivisions.⁸ Sonoran desertscrub hosts a variety of cacti besides the saguaro, including several types of cholla (*Cylindropuntia*), barrel cactus (*Echinocactus*, *Ferocactus*), pin-cushion cactus (*Mammillaria*, *Escobaria*), and organ pipe cactus (*Stenocereus thurberi*).⁹ This landscape contains many areas of low woodland dominated by blue palo verde (*Parkinsonia florida*), foothill palo verde (*Parkinsonia microphylla*), desert ironwood (*Olneya tesota*), mesquite (*Prosopis velutina*, *Prosopis pubescens*), and cat-claw acacia (*Cacia greggii*).⁹ Geologically, SNP is contained within the Basin and Range Physiographic Province.¹⁰ The Tucson and Rincon Mountains' rock formations are metamorphic in origin and comprise the majority of their respective districts. Annual rainfall in the park averages 30 to 35 cm and follows bimodal wet and dry periods with rainfall peaks in the winter and in the summer monsoon period.¹¹

High elevations in the RMD dictate a different biome, sometimes referred to as a "sky island," which includes regions of oak savannah, pine oak forest, woodland, and coniferous forest.¹⁰ Although the shadow detection methodology was applied to the high-elevation regions in RMD, saguaro locations at elevations >1550 m were deleted. The maximum elevation threshold for saguaros has been established as 1500 m.¹¹ An elevation limit of 1550 m was applied to avoid any omission near the threshold and to delete commission in regions that are above the threshold. The elimination of the high-elevation areas reduced the effective size of the study area from 144 square miles (37,296 hectares) to 89.5 square miles (23,180 hectares).

3 Methods

The PAG has compiled fine spatial resolution digital aerial imagery of most of Pima County, including SNP. The imagery has been rectified and projected by PAG. This research used most recent PAG imagery dataset that includes complete coverage of SNP, which was collected in 2011. This imagery has a spatial resolution of 15.24 cm and has been georeferenced to be planimetrically correct. The images contain four spectral bands: blue, green, red, and near-infrared. Although the signature of a saguaro from nadir viewing may only be 2 to 5 pixels at this resolution, the shadows cast by the saguaros tend to be much more easily identifiable due to the long horizontal signature (Fig. 2). Fortunately, the saguaro is relatively unique in its shape and height in the Arizona Upland subdivision of the Sonoran Desert.¹² This enables the use of unique shadow signatures as proxies for saguaro locations.

The saguaro location detection method developed by this research exploits the uniqueness of the shadow signatures produced by the saguaro cactus in the Sonoran desertscrub landscape that comprises the majority of SNP. Direct detection of saguaros from a nadir view angle, even with fine spatial resolution imagery, is not a reliable approach. At full maturity, saguaro diameters reach 30 to 75 cm, which comprise 2 to 5 pixels in the multispectral imagery.¹² In practice, these direct saguaro signatures are not distinct and easily identifiable. A cursory visual examination of the imagery reveals that saguaro shadows are easily recognizable as linear dark regions with a width of ~2 pixels (Fig. 2) that contrast sharply with surrounding nonshadow areas. The length of the shadow depends on solar zenith angle, saguaro height, and local topography. The shadow method presented here relied on saguaro shadows as reliable proxies for saguaro locations.

This research sought to develop an automated process for correctly identifying saguaro shadow signatures. A simple shadow detection method was not sufficient, as other shadows in the imagery were caused by rocky terrain and vegetation. To distinguish saguaro shadows from nonsaguaro shadows, custom search kernels were utilized to ratio shadow regions against adjacent nonshadow regions, with an orientation corresponding to the solar azimuth angle. Edge detection was initially investigated as a method to exploit the linear contrast of the edges of saguaro shadows. Object-based classification was also tested using the Feature Analyst extension of ESRI's ArcMap software. Both approaches failed to yield satisfactory initial results. The



Fig. 2 Sample of natural color multispectral imagery in the TMD of SNP. Long, linear shadow signatures are indicative of saguaro locations.

method presented here was developed to achieve a more customizable and responsive process that would allow for subtle modifications in the pursuit of the highest accuracy possible. The workflow for the saguaro detection is shown in Fig. 3. This process involves using time of image acquisition data to calculate a solar azimuth angle, which is used to build a custom search kernel. The search kernel is used to score pixels based on contrast between shadow and nonshadow regions. A shadow mask is applied to remove duplicates caused by multibranching saguaros. This process is run as a python script that relies on the ESRI's ArcPy library and the Pysolar library developed by Brandon Stafford and collaborators. The script's functionality can be accessed as a script tool using ESRI ArcMap software. The script tool allows the user to specify kernel dimensions and maximum elevation as input parameters. The python code and the script tool are available at: https://github.com/forestcarter/saguaro_detection.

3.1 Calculation of Solar Azimuth Angle

This method relies on a calculated solar azimuth angle to determine the direction a saguaro shadow will fall based on the time, date, and location of the imagery acquisition. The digital aerial imagery [Fig. 3(b)] was acquired over the span of 10 days in late April 2011. The images were taken at various times of day with consequently various solar azimuth angles and corresponding shadow directions. Flight data points [Fig. 3(a)] containing information about the date and time of the raw image acquisition were used to calculate solar azimuth angles [Fig. 3(e)]. This was done using the PySolar Python library developed by Brandon Stafford and collaborators [Fig. 3(c)]. Each flight data point was assigned a solar azimuth angle based on its acquisition time, which was subsequently used to determine the direction of saguaro shadow signatures.

The solar elevation angle in the imagery also varied in accordance with the time of day and date of acquisition. The maximum solar elevation angle for the imagery used was 70 deg, corresponding to imagery taken at 12:30 PM local time on April 21, 2011. The minimum solar elevation angle was 31 deg, corresponding to imagery taken at 8:21 AM local time on April 22, 2011.

As the solar elevation angle increases, the length of saguaro shadows decreases. At solar elevation angles near the maximum of 70 deg, the shadows of short saguaros became increasingly small, making them difficult to separate from ancillary shadows in the image. However,

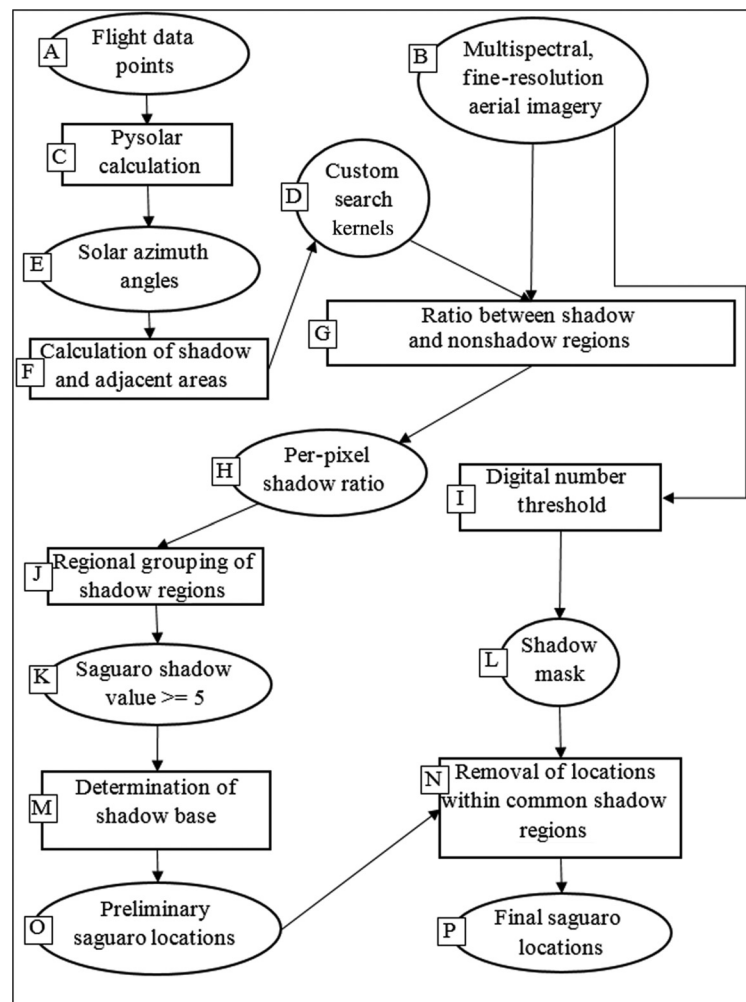


Fig. 3 Overview of saguaro detection methodology and workflow. Ovals represent datasets and rectangles represent processes. Multispectral aerial imagery and flight data points are the primary the inputs. Final saguaro locations are the output.

this effect is partially offset by increased contrast between shadow and nonshadow regions caused by direct solar insolation at high solar elevation angles.

3.2 Per Pixel Shadow Value Calculation

The digital aerial imagery was first clipped to square mile (259 hectares) sections based on Public Land Survey System polygon geometries. A collection of image acquisition data points containing the date and time of each image captured was supplied by PAG staff. These data points were used to build lists of solar azimuth angles within each section. Most of the flight points were often only seconds apart from one another as the airplane from which the images were taken flew over the section in a matter of seconds and took several images. However, some of the imagerys were composed of scenes composited from multiple raw images taken at considerably different times of day. To account for various solar azimuth angles within a scene, repeat scans were run for a section if a flight point existed with a solar azimuth angle that was >10 deg different from the previous scan.

A saguaro shadow ratio [Fig. 3(h)] was determined for each pixel in the imagery using a ratio of the mean digital numbers in three adjacent areas. For each solar azimuth angle, three custom search kernels [Fig. 3(d)] were created. These custom kernels were comprised of one area representing a typical saguaro shadow and two adjacent regions representing contrasting non-shadow areas. Each custom search kernel was defined as a rectangle with a length and

width specified by input parameters, which can be adjusted based on the spatial resolution of the imagery. The search kernels originate from a target pixel and are oriented in the direction of the solar azimuth angle. A width of 2 pixels was chosen by measuring the widths of 30 typical saguaro shadows and taking an average. A length of 10 pixels was chosen as the minimum length that could reliably differentiate saguaro shadows from other shadows in the region. Two nonshadow search kernels were defined as two rectangles identical to the shadow kernel and located directly parallel and adjacent to the shadow kernel and located directly parallel and adjacent to the shadow kernel on either side (Fig. 4).

These custom search kernels [Fig. 3(d)] were used to calculate the mean digital number values of the red band of the images in the neighborhood adjacent to the target pixel. If a saguaro shadow was present, the shadow neighborhood would have a relatively low mean of digital numbers, while a nonshadow region would have a relatively high mean of digital numbers. A ratio of the three regions [Fig. 3(h)] was calculated by dividing the sum of the mean of the nonshadow regions by the mean of the shadow region [Fig. 3(g)]. Each pixel was assigned this ratio as a score. Higher scores were indicative of a saguaro shadow, while lower values were not. Visual inspection revealed that a threshold score of 5 or greater was ideal for identifying the highest proportion of saguaro shadow signatures while limiting false positives due to nonsaguaro shadows in the scene. Pixels with a score below 5 were discarded.

3.3 Using Pixels Scores to Locate the Saguaro Base

Pixels assigned a shadow ratio score of 5 or greater were then grouped into contiguous regions [Fig. 3(k)]. A regional maximum was calculated and stored for each distinct region. The pixel closest to the base of the saguaro was determined to the southwestern most pixel when the solar azimuth angle was $<180^\circ$ deg and the southeastern most pixel when the solar azimuth angle was $>180^\circ$ deg [Fig. 3(m)]. This pixel was given the value of the previously calculated regional maximum, and all other pixels in each region were discarded. This resulted in one pixel with a regional maximum score, indicating a preliminary saguaro location [Fig. 3(o)].

Saguaros with multiple branches often produced multiple point locations, as each branch was identified as an individual saguaro. To correct for this, a shadow mask was applied [Fig. 3(l)] to delete duplicate points that occurred within a common shadow region [Fig. 3(n)]. To create the shadow mask, 30 locations were identified in Section 17 (Fig. 6), where multiple branches were producing multiple saguaro location points. The digital numbers of the shadow areas that linked the branches to the main saguaro stem were recorded. A maximum value of 70 in these measurements was calculated and used to establish a threshold for the shadow mask [Fig. 3(i)].

Pixels with a digital number below 70 were classified as shadow and grouped into regions [Fig. 3(l)]. Within each region, if multiple preliminary saguaro locations existed, the pixel closest to saguaro base was preserved and the others were discarded [Fig. 3(n)].

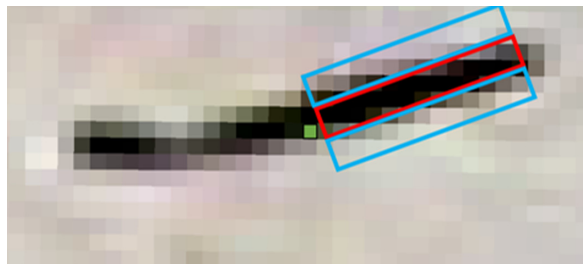


Fig. 4 Example of custom kernels being used to calculate saguaro shadow ratios. A target pixel (green square), a shadow search kernel (red rectangle), and two nonshadow search kernels (blue rectangles) are shown overlaid on a subset of natural color digital aerial imagery with a spatial resolution of 15.24 cm. Shadow ratio scores were calculated for each pixel using the digital numbers of the red band of the imagery. The target pixel received a shadow ratio score calculated as the sum of the mean of the nonshadow search kernels divided by the mean of the shadow search kernel. Pixels with shadow ratio scores of 5 or higher were classified as saguaro shadow pixels.

The remaining pixels were converted into point locations [Fig. 3(p)]. The point locations were assigned an elevation value based on the USGS DEM. Points above 1550 m were deleted, as 1500 m has been shown to be the maximum elevation at which saguaros have been observed.¹¹ All points were merged into a common point geometry file and clipped to the boundaries of SNP. A density map was also produced by overlaying a one-hectare grid on the SNP boundary polygon geometry.

3.4 Establishment of Minimum Height

To compare the shadow method's results against saguaro location data collected by SNP staff, it was necessary to identify the minimum saguaro height that the shadow method was capable of detecting. The shadow method's saguaro location data were compared against the Conver et al.⁵ 2011 to 2012 Section 17 saguaro location and height data to determine a minimum height of saguaros detected. Although the spatial accuracies of saguaro location data in the Conver et al.⁵ Section 17 census were not sufficient for comprehensive individual validation (year 2010 plots were used), identification and matching of some individuals was possible, enabling one-to-one comparisons for minimum height determination. We first isolated all saguaros from the Conver et al.⁵ survey that were between 1- and 2-m tall. From this subset, we identified 100 locations where the shadow method agreed with the Conver et al.⁵ survey data. We then recorded the minimum height as recorded by Conver et al.⁵ from these 100 matching locations. The minimum height identified was 1.5 m. We used this number as the average minimum height, at which the shadow method could reliably detect saguaros, even though the length of shadows cast by 1.5 m saguaros varied with solar elevation angle and local topography.

3.5 Accuracy Assessment and Saguaro Density Calibration

Eleven *in situ* field surveys plots collected by SNP staff in 2010 (Fig. 1) were used to assess the accuracy of the shadow detection method. These data included the heights and locations in 11 plots, 5 in the RMD and 6 in the TMD. The plots varied in size from 0.8 to 1.9 hectares. Saguaros with a height of <1.5 m were discarded. Saguaros with neighbors <1.5 m away were discarded to minimize errors due to proximate saguaros not producing sufficiently distinct shadows for reliable detection. We considered 1.5 m to be the minimum proximity at which saguaros could produce sufficiently distinct shadows to be identified as individuals. Each of the remaining saguaros (1094) in the field data plot was compared to the shadow method points and classified as correct or omitted. The omitted saguaros were divided into three categories:

1. No shadow signature: field survey saguaro produced no shadow signature in the imagery and was not counted by the shadow detection method. These were defined as undetectable by a human analyst.
2. Field survey saguaro produced a weak shadow signature and was not counted by the shadow detection method. These were defined as difficult for a human analyst to identify.
3. Field survey saguaro produced a strong shadow signature but was not counted by the shadow detection method. These were defined as easily identifiable by a human analyst.

Errors of commission were identified as locations at which the shadow method detected a saguaro signature, but no saguaro was recorded in the field surveys. This occurred when a rock, plant, or other object on the landscape produced a shadow that was sufficiently similar to a saguaro shadow as to be detected and marked by the shadow method.

The results of the shadow methods can be calibrated to correct for omission and commission errors. A regression equation was obtained by applying a linear regression to the shadow method results and the mature saguaro field survey data in the 11 SNP plots from 2010. The resulting equation can be used to adjust the results of the saguaro method to predict actual densities of mature saguaros per hectare.

3.6 Fieldwork to Identify Missing Saguaros

The results of the accuracy assessment show that 21% of mature saguaros produced no shadow signature in the imagery. This prompted an investigation into possible explanations for these

omissions. Of the 11 SNP plots, 2 were chosen as our fieldwork sites due to their accessibility, representation of both districts of the park, and feasibility of locating all of the missing saguaros within the site. Site 8, which contained 19 missing saguaros, and site 6, which contained 25 missing saguaros, were visited in December 2017 (Fig. 1).

For this fieldwork, we first isolated the SNP point locations that were identified as not producing shadows in the imagery. We uploaded the SNP location and height data for these points to a GPS-enabled Apple iPad tablet. We used these data in the field to locate the individual saguaros. For each location, we surveyed the surrounding area for possible causes the saguaro shadow being obscured. We recorded one or more possible causes for each location and photographed each scene.

4 Results and Discussion

4.1 Saguaro Density and Distribution

Our automated saguaro survey of SNP detected 446,092 saguaro shadows across 23,180 hectares of SNP. Densities ranged from 0 to 196 per hectare, with a mean density of 19.3 saguaros per hectare and a standard deviation of 22.8. No saguaros were detected in 3726 hectares, equal to 15% of the total area. Density maps were created by dividing each park district into one-hectare cells. The number of saguaros in each hectare cell is shown by a pseudocolor gradient scheme (Figs. 5 and 6).

The saguaro density maps produced from this automated survey (Figs. 5 and 6) offer the first view of saguaro density distributions in all of SNP. This map will be of interest to SNP to be able to easily show park visitors where saguaro density is at its highest. The peak density regions of the TMD that are rarely visited may be of interest to interpretive staff at SNP. Researchers studying saguaro ecology and population dynamics will be able to identify significant patterns in density that correlate strongly with physical or biological variables in the landscape. The distribution of saguaro locations on such a large extent has not been previously analyzed. This distribution may yield critical insight into the relationship of saguaros to the surrounding biotic and abiotic environment. These data can be used as a snapshot of the saguaro population in time, which can be compared to new data each time new imagery is acquired.

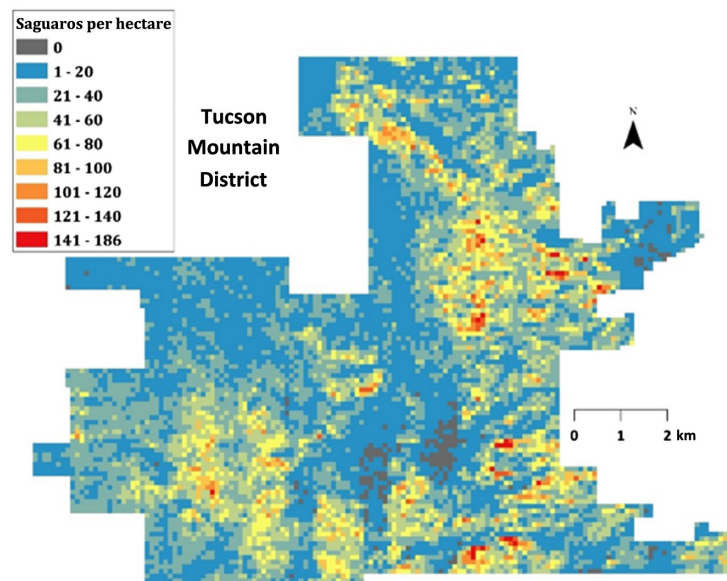


Fig. 5 Shadow method results of saguaro density per hectare in TMD of SNP in 2011.

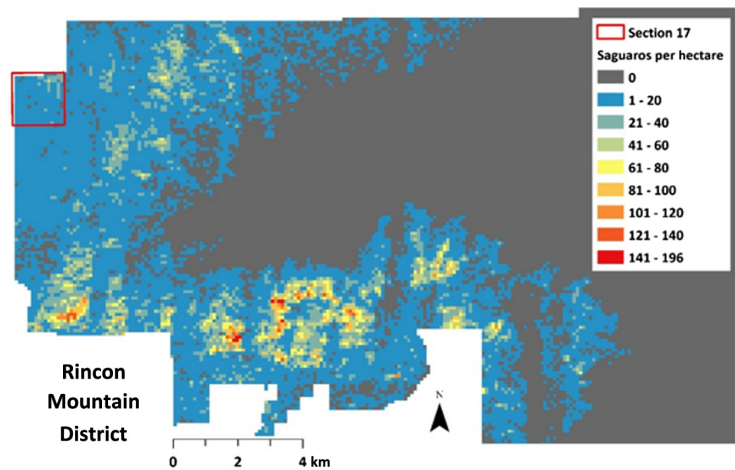


Fig. 6 Shadow method results of saguaro density per hectare in RMD of SNP in 2011.

4.2 Accuracy Assessment

Omission occurred where saguaros were present in the 11 SNP plots but were not detected by the shadow method. Of the 1094 mature saguaros that were recorded in the 11 SNP plots collected by staff in 2010, 639 (58%) were correctly identified, 235 (21%) were omitted and classified as no signature, 140 (13%) were omitted and classified as weak signature, and 80 (7%) were omitted and classified as strong signature (Table 1). The summation of the three types of omission error produces the total omission error. Plot 1 had the lowest omission rate at 30%, while plot 7

Table 1 Validation results (omission errors). Saguaro location data in 11 plots collected by SNP staff in 2010 were compared against the results of the shadow method applied to 2011 imagery. Omission occurred where a saguaro was located in the field survey plots but was not detected by the shadow method. The overall omission rate was 42.9%.

Site number	Area (hectares)	Saguaros in field survey	Saguaros correct	Saguaros omitted—no signature	Saguaros omitted—weak signature	Saguaros omitted—strong signature	Omission percentage
1	1.32	10	7	2	1	0	30.0
2	0.82	22	11	7	4	0	50.0
3	1.58	34	19	11	2	2	44.1
4	1.64	38	20	15	1	2	47.4
5	1.97	81	42	23	11	5	48.1
6	1.57	88	51	25	7	5	42.0
7	1.72	105	41	24	23	17	61.0
8	1.78	132	85	19	17	11	35.6
9	1.83	176	104	32	26	14	40.9
10	1.84	196	121	36	24	15	38.3
11	1.85	212	138	41	24	9	34.9
Total	17.9	1094	639	235	140	80	NA
Mean	1.63	99	58	21	13	7.3	42.9
SD	0.32	71.8	46.5	12.1	10.3	6.23	8.58

had the highest omission rate at 61%. The overall omission error for all 11 SNP plots was calculated to be 42%. This translates to a producer's accuracy of 58%.

The 21% of saguaros that were omitted due to a lack of signatures represent errors that were unavoidable using this imagery and the SNP validation plots. Uncertainty in the GPS data of the plots may have caused some of this error, as a misplaced location would be classified as no signature. Mature saguaros may not produce shadow signatures due to various sources of shadow obscuration, which we investigated in our fieldwork.

The 13% of omitted saguaros that produced a weak signature and the 7% of omitted saguaros that produced a strong signature represent the areas where refinement of the shadow method may be able to increase accuracy. Weak signatures are difficult to detect, as a method that is sensitive to weak signatures becomes increasingly susceptible to false positives caused by nonsaguaro shadows in the imagery.

Commission occurred where the shadow method placed points where no saguaro was found in the SNP plots. Of the 695 mature saguaros that were detected by the shadow method in the SNP plots, 56 were identified as erroneously committed. Plot 6 had the lowest commission rate at 3.8%, while plot 1 had the highest rate with 22.2% (Table 2). The overall commission error for all 11 plots was calculated to be 8.1%. This translates to a user's accuracy of 91.9%. Commission errors vary with the sensitivity level in the method's design. The shadow method used a threshold value of 5 when selecting pixels based on the calculated shadow ratio score. Using higher values for this threshold would decrease commission, as only very strong saguaro shadows would be identified. However, omission would increase, as short saguaro shadow and weak signatures would not be detected. A threshold value of 5 was used to balance commission and omission errors to yield the most accurate detection of saguaro locations.

Table 2 Validation results (commission errors). Saguaro location data in 11 plots collected by SNP staff in 2010 were compared against the results of the shadow method applied to 2011 imagery. Commission errors occurred where a saguaro was located by the shadow method but was not present in the field survey plots. The overall commission rate was 8.1%.

Site number	Area (hectares)	Saguaros detected by shadow methodology	Saguaros correct	Saguaros committed erroneously	Commission per hectare	Commission percentage
1	1.32	9	7	2	1.52	22.2
2	0.82	13	11	2	2.44	15.4
3	1.58	23	19	4	2.54	17.4
4	1.64	21	20	1	0.61	4.8
5	1.97	46	42	4	2.03	8.7
6	1.57	53	51	2	1.27	3.8
7	1.72	45	41	4	2.33	8.9
8	1.78	95	85	10	5.63	10.5
9	1.83	110	104	6	3.28	5.5
10	1.84	132	121	11	5.97	8.3
11	1.85	148	138	10	5.42	6.8
Total	17.91	695	639	56	NA	NA
Mean	1.63	63	58	5.09	3.00	10.20
SD	0.32	49.7	46.4	3.48	1.77	5.53

4.3 Fieldwork to Identify Missing Saguaros

The goal of the fieldwork was to investigate the reasons why these saguaros failed to produce shadow signatures in the images. Three possible causes were identified: shadow alignment, vegetation interference, and rocky slope interference (Fig. 7). Shadow alignment occurred when the shadow of one saguaro fell onto another individual in such a way that the shadow method was unable to parse them as separate individuals. Vegetation interference occurred when a saguaro shadow was obscured by the surrounding vegetation and was therefore not detected by the shadow method. Rocky slopes also obscured, shortened, or distorted some saguaro shadows and prevented the shadow method from detecting them. We located 41 of 44 missing saguaros in sites 6 and 8. Three saguaros were not found, possibly due to GPS location uncertainties or saguaro mortality between 2010 and 2017.

Vegetation interference was determined to be a factor in 25 of the 41 located saguaros (61%). Rocky slope interference was determined to be a factor in 22 of the 41 saguaros located (54%). Shadow alignment was determined to be a factor in 8 of the 41 saguaros located (20%).

These results show the most common causes of saguaro shadow absence in the aerial imagery. The high rate of vegetation interference is not surprising due to the tendency of mature saguaros to often be located near larger vegetation that once served as “nurse trees.”¹³ A high rate of rocky slope interference is expected in foothill areas and mountainous terrain that comprise the majority of both TMD and RMD. Shadow alignment rates are expected to be high where saguaro densities are high. These factors are uncertainties inherent in the reliance on shadows as proxies for saguaro locations.

4.4 Shadow Method Results Compared to Field Survey Data

The overall accuracy of the shadow method compared to mature saguaros in the 11 SNP plots was 58%. A strong linear correlation (R^2 value of 0.9611) is present between the shadow method results and the mature saguaro field survey data (Fig. 8). This strong correlation indicates that the shadow method provides a reliable relative density measurement. Although only 58% of the total number of saguaros is detected on average, the shadow method reliably predicts the relative density of each hectare compared to the population as a whole. Although the shadow method underestimates mature saguaro populations due to the factors discussed in Sec. 4.3, the rate of underprediction is consistent, as shown by the strong correlation in Fig. 7. Therefore, the linear regression equation shown in Fig. 8 can be used to calibrate results for the shadow method to estimate total mature saguaros per hectare.

4.5 Areas of Low Accuracy

Field plot 7 was shown to have the lowest producer's accuracy of the 11 plots. Visual inspection of the strong and weak shadow signatures that were not detected by this shadow method showed

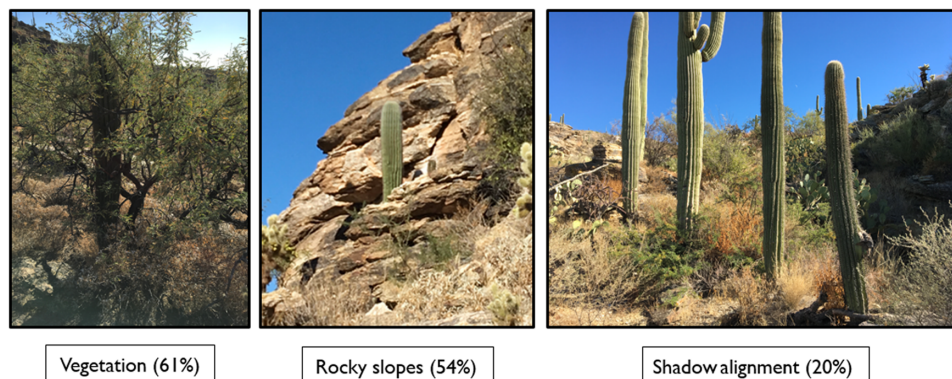


Fig. 7 Images captured in SNP illustrating common cause of saguaro shadow absence in aerial images.

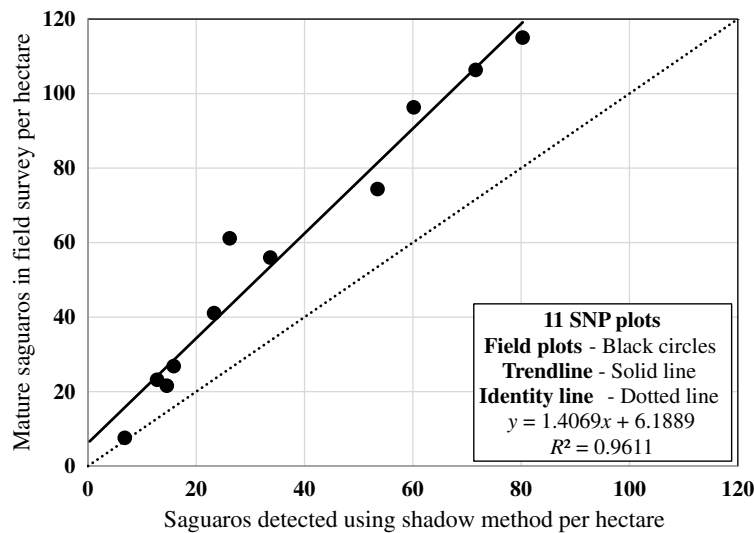


Fig. 8 Scatterplot of saguaros detected by the shadow method compared with field surveys of mature saguaros in Section 17 (solid circles) and in 11 spatially distributed SNP plots (open circles). Trend lines are shown as solid and dashed lines, respectively. Each hectare is displayed as a point with an x value representing the number of saguaros identified from 2011 imagery by the shadow method and a y value representing the number of mature (>1.5 m in height) saguaros identified by *in situ* field surveys. An identity line (1:1 line) is shown as a dotted line.

signatures that were much shorter in length than in other images. The imagery for this region was acquired at 12:44 PM on April 21, 2011, with a calculated solar elevation angle of 68 deg. If the time of acquisition is close to local noon (12:27 PM), as was the case for plot 7, the solar elevation angle will be near its highest point, resulting in shadows that are shorter and less distinctive in shape. This problem will be more severe when the date of acquisition is close to the summer solstice (June 21) or at lower latitudes. Plot 7 is a representative of the reduced accuracy that will occur from imagery acquired at times of high solar elevation angles. For the purposes of this research, imagery acquired at times when the solar elevation angle is more acute would be advantageous, as longer shadows enable more reliable identification of shorter saguaros. When future imagery is acquired, we recommend acquisition times at least one hour before or after local solar noon, as this would increase the proportion of the saguaro population that is detectable using shadow signatures.

4.6 Automation versus Visual Interpretation

The shadow method was designed to be automated and not require visual interpretation by a human analyst. An alternative approach would be to use a human analyst to identify saguaro locations from the imagery. This method would likely be a more accurate method of saguaro location identification, as it is difficult to match the pattern recognition abilities of the human brain with an algorithm.¹⁴ However, analyzing large areas such as SNP would require several weeks of labor for a human analyst. This amount of labor and expense would likely render the project unfeasible due to budgetary constraints of SNP. In addition, new labor expenses would be incurred for every new set of imagery that is collected. The automated shadow method presented here seeks to be sufficiently adjustable, accessible, and inexpensive so that land managers can implement it on future imagery and in other areas within the saguaro's range.

5 Conclusion

The primary motivation of this research was to develop an automated saguaro detection tool that would be useful to resource managers at SNP. This research explored the feasibility of automatically mapping individual saguaros using shadow signatures in fine-resolution digital aerial

imagery. We developed a method that scored individual pixels (15.24 cm) based on the ratio of adjacent shadow and nonshadow regions. The results of this methodology were compared to *in situ* field survey data collected by SNP to assess accuracy. We investigated reasons why no shadow signature was produced for 41 saguaros in two locations. Vegetation interference, rocky slope interference, and shadow alignment were found to be the primary causes of saguaros producing no shadow signature in the imagery.

This method correctly identified 58% of saguaros taller than 1.5 m. Twenty-one percent produced no shadow signature, 13% produced a weak shadow signature that the shadow method did not detect, and 7% produced a strong signature that the shadow method did not detect. Several possible refinements of the methodology can be further explored, which could improve the accuracy of the results when compared against *in situ* field surveys.

The shadow methodology presents several opportunities for further study:

- (a) Application in other areas: Although our study area was limited to the boundaries of SNP, this method could be applied to other areas in the saguaro's range. Other sites that have been the focus of intensive saguaro research, such as the "Desert Lab" on Tumamoc Hill in Tucson, could use the shadow methodology to supplement ongoing studies.
- (b) Time-series analysis: One of the most compelling applications of the shadow methodology could be the identification of changes in saguaro populations over time. Although this research was limited to imagery taken in April 2011, past imagery could be analyzed with the shadow method and compared to 2011. This would enable easy identification of areas where the saguaro population has changed over time. Similarly, if new imagery is collected in the future, the shadow method can be easily applied to each new dataset, producing decades of saguaro data over large areas. Identification of areas of significant change could help identify study sites for *in situ* data collection and further research.
- (c) Analysis of factors that affect saguaro density: The density map produced by the shadow method could be useful in the study of the factors that control saguaro reproduction, survival, and growth rates. Patterns in soil composition, slope, aspect, elevation, and presence of other vegetation species may have significant effects on saguaro density. Using the shadow method's density map for large areas could reveal patterns that were not visible when analyzing small plots.

This research builds upon the long history of saguaro monitoring and research at SNP. Although the shadow method only detects mature saguaros that cast a sufficiently distinct shadow, the results were shown to be representative of the total saguaro population. The automated saguaro shadow detection method provides a valuable tool for SNP resource managers and other researchers and stakeholders to conduct large extent saguaro censuses with a minimal investment of time and money. This research suggests that saguaro mapping over large areas can inform future strategic land management decision-making and help produce a more complete understanding of this unique and inspiring species.

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