

MAPPING SAGUARO CACTI USING DIGITAL AERIAL IMAGERY IN SAGUARO  
NATIONAL PARK

by

FOREST CARTER

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A Thesis Submitted to the Faculty of the

SCHOOL OF GEOGRAPHY AND DEVELOPMENT

In Partial Fulfillment of the Requirements for the Degree of

MASTER OF ARTS

WITH A MAJOR IN GEOGRAPHY

In the Graduate College

THE UNIVERSITY OF ARIZONA

2018

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## **ACKNOWLEDGEMENTS**

I would like to thank my academic advisor Dr. Willem van Leeuwen for his support and indispensable advice throughout this project and my graduate education. Dr. Greg Barron-Gafford and Dr. D. Philip Guertin also have my sincere gratitude for providing insightful feedback as committee members. Thanks to Dr. Adam Springer of Saguaro National Park for proposing this project and supervising me during my assistantship. I would also like to thank Georgia Ehlers of the University of Arizona Peace Corps Coverdell Fellows program for helping to put me in an environment where I could succeed.

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## ABSTRACT

The saguaro cactus has been the subject of extensive ecological research since the establishment of Saguaro National Monument in 1933. Saguaro mapping and monitoring has always been limited in extent due to inherent restrictions of *in situ* field methods. This research developed a method for automated mapping of mature saguaros over large extents using fine spatial resolution digital aerial imagery. Saguaro shadow signatures were identified using a novel contrasting custom search kernel method. The shadows detected were used as proxies for mature saguaro locations.

This research focused on (1) the development of a method of automatically identifying saguaros using their shadows in aerial imagery, (2) applying the method to aerial imagery of Saguaro National Park (SNP) to conduct a large extent saguaro census, (3) validation of the saguaro distributions against *in situ* field measurements, (4) investigating causes of shadow omissions, (5) estimating total saguaro densities and populations in SNP. The shadow method developed identified 446,092 saguaros across 231 square kilometers in Saguaro National Park. These results were found to be highly correlated ( $R^2$  value of 0.966) with saguaro locations recorded by SNP staff in 11 field plots in 2011. This study demonstrates that mature saguaros can be reliably mapped automatically using digital aerial imagery. The method developed will facilitate saguaro monitoring and ecological resource management in SNP and throughout the range of the saguaro cactus.

## INTRODUCTION

The saguaro cactus (*Carnegiea gigantea*) is perhaps the most recognized and iconic member of the cactus family (*Cactaceae*). The saguaro's impressive height, unique branching patterns, and high densities in otherwise sparsely vegetated areas produces awe-inspiring landscapes unique to the Sonoran Desert. The fact that the saguaro's range is limited almost exclusively to the Sonoran Desert of the American Southwest and Northern Mexico makes this charismatic mega-flora an iconic symbol of the region.

The saguaro is deeply enmeshed in the identity of the state of Arizona and the city of Tucson. Nowhere is this more apparent than in the 144 square miles of federally protected land around Tucson appropriately named Saguaro National Park (SNP). Established as a National Monument in 1933 to protect a particularly stunning stand of saguaros, SNP has served as an epicenter of saguaro research for nearly a century. SNP is currently composed of two separate districts: Tucson Mountain District (TMD) on the west side of Tucson and Rincon Mountain District (RMD) on the east side of Tucson. Observations of dramatic saguaro population fluctuations in RMD originally catalyzed intensive saguaro research beginning in the 1940s (Steenbergh and Lowe 1969). Those studies began a legacy of ecological research into the dynamics of saguaro biology and ecology that continues today (McAuliffe 1993).

Saguaro research in SNP and other areas of the Sonoran Desert has produced a remarkable body of knowledge, especially considering that intensive studies of individual plants species are usually aimed at agricultural applications. Concern regarding the health of saguaro populations motivated some of the earliest research efforts and has been an enduring impetus for decades (Shreve 1910). Concern became panic in the early 1940s when an infectious “pathogenic disease” was reported to pose a substantial threat to healthy saguaro populations in

SNP (McAuliffe 1993). Although the symptoms of the supposed disease were later identified as effects of the natural decomposition process of older individuals, efforts to eradicate the pathogen catalyzed a campaign of saguaro research and monitoring that has yielded many critical insights into the lifecycle of the saguaro cactus.

Long-term saguaro monitoring began at SNP with an effort to measure the efficacy of a disease suppression experiment in 1941 (Gill and Lightle 1942). The experiment involved the removal of 313 saguaros displaying supposed symptoms of the disease in a one square mile section in the northwest corner of what is now the Rincon Mountain District of SNP (McAuliffe 1993). This area, known as “Section 17”, was surveyed for saguaros in its entirety in 1941, and was resurveyed in 2011-2012 (Gill and Lightle 1942, Conner et al. 2017). Several smaller plots within Section 17 have been monitored on an annual basis, creating a 75-year record of the saguaro population (Orum et al. 2016). On a larger extent, 45 small plots were established in 1989 throughout both districts of SNP by Duriscoe and Graban (1992), which were later resurveyed by Funicelli et al. (2000). These saguaro monitoring efforts have produced valuable knowledge regarding saguaro density, mortality, regeneration, recruitment, and demography (Steenbergh and Lowe 1969, Funicelli et al. 2000, Orum et al. 2016).

Many vital conclusions regarding the biology and ecology of the saguaro have resulted from research within SNP. The factors that dictate saguaros seedling establishment were found to be heavily dependent on soil, precipitation, insects, and rodents (Steenbergh and Lowe 1969). Saguaro populations were shown to be controlled by survival in the juvenile life stages when drought, freezing events, and soil disturbances may cause high mortality rates (Steenbergh and Lowe 1977). Crucial protection from direct solar radiation and dramatic temperature fluctuation is often provided by “nurse plants” or “nurse rocks” (Steenbergh and Lowe 1977, Drezner 2003).

The age of saguaros is notoriously difficult to measure, so long-term research into the relationship between age and height has been critical for understanding population and growth dynamics (Steenbergh and Lowe 1977, Drezner and Lazarus 2008).

The impact of human activities on saguaro populations has also been the subject of several research efforts. Wood cutting and cattle grazing before the establishment of the National Monument and the enforcement of preservation laws significantly changed the ecology of SNP and the population structure of saguaros (McAuliffe 1993, Niering et al. 1963). Air pollution in the form of increased ozone concentration and sulfur emissions leading to acid rain have been documented in the greater Tucson area, although a concrete effect on saguaro populations has not been established (McAuliffe 1993). Global greenhouse gas emissions are likely to cause long-term temperature, precipitation, erosion changes in the American Southwest (Archer and Predick 2008). The exact effects of these changes on saguaros are unknown. However, given the sensitivities of young saguaros to these environmental variables, dramatic changes in saguaro populations are possible.

Saguaro research has historically been limited to study areas of small to medium-sized extents. The study areas of long-term monitoring plots are based on small extents, usually 1-5 hectares. Two medium extent (one square mile) saguaro censuses have been completed in Section 17, first by Gill and Lightle (1942) and again by Conner et al. (2017). Large extent saguaro monitoring on a scale of many square miles has not been attempted. The use of traditional *in situ* field surveys techniques requires a large amount of time, labor, and funding that increases as size of the study area is expanded. This renders the possibility of large extent saguaro monitoring using *in situ* methods extremely difficult and expensive. Saguaro monitoring of large areas would enable new analyses of population dynamics and density variability that are

not feasible in small and medium extent studies. This research seeks to perform large extent saguaro monitoring by mapping saguaro locations from digital aerial imagery. Using shadows as proxies for saguaro locations, this research will automate large extent saguaro mapping. This will enable new research into saguaro ecology and serve as a useful decision-making tool for SNP staff and other land managers.

## **PRESENT STUDY**

The paper appended to this thesis presents the methods, data, results, discussion, and conclusions of this research. Important findings of the paper are summarized here.

### **I. Summary**

The primary objective of this research was to develop a reliable methodology for automatic identification of mature saguaros in fine spatial resolution digital aerial imagery. We developed and applied a novel methodology to aerial imagery of Saguaro National Park to conduct a saguaro census of 89.5 square miles (231 square kilometers) within SNP. In support of the primary objective, this research also assessed the accuracy of the methodology by comparing results against saguaro location data collected by SNP staff in long-term monitoring efforts. A large proportion of the mature saguaro population (21%) were found to not have produced a shadow signature in the imagery, which prompted a field study to investigate possible causes of shadow omission. We used the results of the accuracy assessment to estimate mature saguaro densities and populations. We also used the SNP monitoring data to estimate total saguaro population including immature saguaros.

Aerial imagery has been utilized to a limited extent to map saguaro locations. However, automated, large extent application has not previously been attempted. Gill and Lightle (1942) used visual interpretation to map saguaro locations in one-square mile (Section 17) of SNP. This research sought to automate the detection of saguaros in aerial images to eliminate the need for labor and time of a human analyst. This would encourage land managers to conduct large extent saguaro censuses using future imagery, thereby building a long-term, large extent time series of saguaro populations and distributions.

This research presents a novel shadow detection method that exploits the high contrast and

uniform shape of saguaro shadow signatures to enable reliable automatic detection. We used the red band of the digital imagery because it provided the highest contrast between shadow and non-shadow regions. Although saguaros are not the only objects that cast shadows in the desert scrubland landscape, the shape of unobscured mature saguaro shadows are relatively unique and easily distinguishable.

The shadow method (Appendix A, Figure 3) scores pixels based on the ratio between neighboring shadow and non-shadow regions. Shadow regions are defined as 10 pixel (150.24 cm) by 2 pixel (30.48 cm) rectangles with a base located at the target pixel (Appendix A, Figure 4). The angle of the shadow region is determined by the solar azimuth angle of the imagery being analyzed. Non-shadow regions were defined as two rectangles identical to the shadow region, placed parallel to the shadow region, adjacent on either side (Appendix A, Figure 4). The mean of the digital numbers of the red band of the non-shadow regions were summed and divided by the mean of the digital numbers of the red band of the shadow region to produce a shadow ratio score for the target pixel. All pixels were given a shadow ratio score using this calculation. Pixels with scores below 5 were discarded.

Pixels with high ratio scores (greater than 5) were grouped into contiguous regions and labeled as saguaro shadows. To remove duplicates caused by saguaros with multiple branches, a shadow mask was applied. Point locations were limited to one per common shadow regions, so each saguaro shadow had a maximum of one point location, even if multiple branches had produced multiple points. Finally, points above 1550 meters in elevation or outside of the boundaries of SNP were deleted.

We compared the shadow method results against 100 saguaro locations collected by Conner et al. (2017) in Section 17 of the Rincon Mountain District to establish a minimum

detectable height. We found that the shadow method was able to reliably detect saguaros with heights greater than 1.5 meters. We refer to saguaros taller than 1.5 meters as mature, and saguaros shorter than 1.5 meters as immature.

This methodology was applied to 89.5 square miles (23,180 hectares) of SNP to create a large extent mature saguaro census. 446,092 mature saguaro shadows were identified. A grid of one-hectare squares was overlaid on SNP boundaries to facilitate analysis. Mean density was found to be 31.8 mature saguaros per hectare with a standard deviation of 24.1 in TMD and 14.4 saguaros per hectare with a standard deviation of 18.6 in RMD. 3,615 hectares were found to have 0 saguaros. The highest saguaro density in a single hectare was 196.

To assess the accuracy of the shadow method, we compared 1,094 mature saguaro locations from SNP monitoring efforts to the shadow method's results. Across the 11 plots of SNP data, the shadow method correctly identified 58% of saguaros. We divided the 42% that were not correctly identified into three categories: no shadow signature (21%), weak shadow signature (13%), and strong shadow signature (7%).

The finding that 21% of mature saguaros failed to produce shadows in the aerial imagery prompted us to conduct fieldwork to investigate possible causes of saguaro obfuscation and preclusion. We located 41 of these "missing" saguaros in two plots and recorded possible factors in the landscape that could prevent a shadow from appearing in aerial imagery. Shadow alignment, vegetation interference, and rocky slopes were identified as the major causes of mature saguaro shadows not appearing in aerial imagery. Shadow alignment was found to be a likely factor in 20% of cases, vegetation interference in 61% of cases, and rocky slopes in 54% of cases.

We used the relationship between the shadow method results and saguaro locations in the

11 SNP plots to estimate saguaro density per hectare and total count in SNP for mature saguaros and populations of both mature and immature saguaros. We used a weighted mean of the 11 plots to obtain commission and omission rates and variances, which enabled estimation of total saguaro populations. We also weighted the proportion of immature to mature saguaros based on the number of saguaros in each plot to establish a ratio of mature saguaros to total saguaros. After correcting the shadow method's saguaro per hectare density results for omission and commission, we estimated an actual mature saguaro density of 50.9 in TMD and 26.5 in RMD with standard deviations of 38.7 and 30.4, respectively. Using the calculated proportion of mature saguaros to total saguaros, we estimated a total of 132.0 saguaros per hectare in TMD and 102.6 saguaros per hectare in RMD with standard deviations of 183.6 and 69.2, respectively. We adjusted the shadow method's total shadow count for commission and omission to estimate a total mature saguaro count of 748,626 in SNP, with a calculated standard error of 75,260. We used the shadow method's previously calculated mature to total saguaro population ratio to estimate 2,284,623 total (mature and immature) saguaros in SNP with a calculated standard error of 200,009.

## II. Conclusions

We concluded from this research that mature saguaros can be mapped automatically and reliably using fine spatial resolution aerial imagery. The shadow method can be employed to map saguaros in large extents quickly and easily. The results of the shadow method are consistent when compared to *in situ* field measurements. Errors of commission and omission are relatively predictable and can be factored in to estimates of the total saguaro population in SNP. Estimation of saguaro densities and total population were consistent with estimations made by other researchers using extrapolation based on small survey plots. We recognized that this shadow method has limitations due to landscape features that block or obscure saguaro shadows. The reported results show that this shadow method will be useful to land managers as a tool to efficiently conduct large extent mature saguaro censuses which can inform research and resource management.

## III. Future work

- i. **Opportunities for refinement of saguaro detection method** - Although the shadow method produced consistent results, we acknowledge that several opportunities of refinement could improve the accuracy and reliability. The primary refinement opportunity is a process for adjusting the custom search kernels for a dynamic solar elevation angle. The current method uses a calculated solar azimuth angle to determine angle of orientation of the search kernels but does not factor in the solar elevation angle. Ideally, the shadow method would adjust the search kernels to be shorter for high solar elevation angles and longer for low solar elevation angles. This would make the method more responsive as shadow lengths vary due to time of day, season, and latitude. The solar elevation angle in the imagery used in this research ranged from a minimum 31°, of

to a maximum of 70°. Accounting for variances in solar elevation angle would likely reduce the omission and commission uncertainties of the shadow method.

- ii. **Application of shadow detection methodology to other dates and places** - The shadow method was designed to be easily implemented on new imagery. Currently existing imagery of other areas within the saguaro's range could be used to conduct large extent saguaro censuses outside of SNP. In addition, if similar aerial imagery is acquired in the future, the shadow method can easily be applied to produce a comparative dataset. This would enable time series analysis of saguaro population, which could yield important insights into the factors that control saguaro population dynamics.
- iii. **Using the shadow method results to target areas for further research:** The shadow method results provide a valuable tool for researchers who seek to conduct field studies on saguaro populations. Researchers could easily select study sites based on mature saguaro density, clustering, or distribution. Using the shadow method's results in conjunction with a digital elevation model would enable further customization based on elevation, slope, or aspect. Researchers could easily establish study plots according to desired variables in pursuit of further knowledge of those factors that influence saguaro populations.

## REFERENCES CITED

- Archer, S. and Predick, K. (2008) Climate Change and Ecosystems of the Southwestern United States. *Rangelands*, 30(3), 23-28. Retrieved from <http://www.jstor.org/stable/25145389>
- Conver, J. L., Foley, T., Winkler, D. E., and Swann, D. E. (2017) Demographic changes over 70 years in a population of saguaro cacti (*Carnegiea gigantea*) in the northern Sonoran Desert. *Journal of Arid Environments*, 139, 41–48.  
doi.org/<http://dx.doi.org/10.1016/j.jaridenv.2016.12.008>
- Duriscoe, D. M. and Graban, S. L. (1992) Epidermal browning and population dynamics of giant saguaros in long-term monitoring plots. Proceedings of the Symposium on Research in Saguaro National Monument, 23-24 January 1991. Southwest Parks and Monuments Association, Globe, Arizona.
- Funicelli, C. S., Anning, P. J., and Turner, D. S. (2000) Long-term vegetation monitoring at saguaro national park: A decade of change. Tucson, Arizona: United States Geological Survey, Western Ecological Research Center, Sonoran Desert Field Station and School of Renewable Natural Resources, University of Arizona.
- Gill, L.S. and Lightle, P.C. (1942) Cactus disease investigations: an outline of objectives, plans, and accomplishments on project j-2-8. Report to the Bureau of Plant Industry. In: Steenbergh, W.F., Lowe, C.H. (Eds.), *Ecology of the Saguaro III. Growth and Demography*. Scientific Monograph Series. Number 17, vol. 1983. National Park Service, Washington DC.
- McAuliffe, J. R. (1993) Case Study of Research, Monitoring, and Management Programs Associated with the Saguaro Cactus (*Carnegiea Gigantea*) at Saguaro National Monument, Arizona. National Park Service, Cooperative National Park Resources Studies Unit, School of Renewable Natural Resources, The University of Arizona.
- Orum, T. V, Ferguson, N., and Mihail, J. D. (2016) Saguaro (*Carnegiea gigantea*) Mortality and population regeneration in the cactus forest of Saguaro National Park: seventy-five years and counting. *PLOS ONE*, 11(8), 1–21. <https://doi.org/10.1371/journal.pone.0160899>
- Shreve, F. (1910) The rate of establishment of the giant cactus. *The Plant World*, 13(10), 235-240. Retrieved from: <http://www.jstor.org/stable/43476815>
- Steenbergh, W. and Lowe, C. (1969) Critical Factors During the First Years of Life of the Saguaro at Saguaro National Monument, Arizona. *Ecology*, 50(5), 825-834.  
doi:10.2307/1933696

Steenbergh, W., and Lowe, C. (1977) Ecology of the saguaro: II, Reproduction, germination, establishment, growth, and survival of the young plant. Washington D.C. Dept. of the Interior, National Park Service.

## APPENDIX A

### MAPPING SAGUARO CACTI USING DIGITAL AERIAL IMAGERY IN SAGAURO NATIONAL PARK

*To be submitted to “Journal of Applied Remote Sensing”*

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## ABSTRACT

The saguaro cactus (*Carnegiea gigantea*) is emblematic of the American Southwest and is considered a valuable natural resource by residents, tourists, and land managers throughout the Sonoran Desert. Despite being one of the most intensively researched non-agricultural plant species, many aspects of saguaro ecology are not fully understood. Dramatic declines documented in several locations have motivated further research into saguaro demographics and growth dynamics. Research on the saguaro has historically been limited to repeat monitoring efforts in small plots with areas of 1-4 hectares. Large extent saguaro censuses of areas greater than one square mile have not been undertaken due to the logistical and financial limitations. The primary objective of this research is to examine the application of fine spatial resolution aerial multispectral imagery to map mature saguaros on a large extent. Specifically, this research used shadows as proxies for the detection of mature saguaros. Mature saguaros were defined as being at least 1.5 meters tall and therefore capable of casting a reliably detectable shadow. Saguaro National Park (SNP) near Tucson, Arizona was used as our study site. This research developed an automated methodology for detecting mature saguaros in digital aerial imagery by using saguaro shadows as proxies for saguaro locations. 446,092 saguaro shadows were detected across 89.5 square miles of SNP. 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. 21% of the saguaros in the plots did not produce a shadow signature in the imagery. We conducted fieldwork in two locations to investigate why these mature saguaros failed to produce shadow signatures in the aerial imagery. We found 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.

## 1. INTRODUCTION

The saguaro cactus (*Carnegiea gigantea*) is a columnar cactus found almost exclusively in the Sonoran Desert. Saguaros are known for their impressive heights, spiny exteriors, multiple branches, and habitat cavities. Saguaros often grow to over 9 meters in height, over 40 centimeters in trunk diameter, and can live to over 200 years old (Niering et al. 1963). Young saguaros are slow growing and may take 50 years to reach one meter in height (Niering et al. 1963). The survival of young saguaros is heavily dependent on biotic factors such as birds, rodents, and insects as well as abiotic factors such as soil composition, precipitation, and shade from “nurse plants” or “nurse rocks” (Steenburgh and Lowe 1969). Saguaro populations rely heavily on seedling establishment and survival rates of during the first 10 years of life (Turner et al. 1966, Steenburgh and Lowe 1969). Efforts to understand the biotic and abiotic variables that affect saguaro population regeneration are hampered by the slow and episodic nature of saguaro demographic change (Pierson et al. 2013).

Natural resource managers, residents, tourists, and researchers consider the saguaro to be a valuable natural resource worthy of scientific inquiry and preservation. The aesthetics of a desert landscape dominated by towering multi-arm 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 symbol (Bruhn 1971) and as an ecological keystone species (Drezner 2014) are well documented. Desire to protect and preserve the saguaro were 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 (McAuliffe 1993). 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 (McAuliffe 1993).

A key method used in the modern era of saguaro research is the systematic monitoring of long-term plots. Long-term monitoring has been instrumental in describing the roles of seedling establishment, growth, mortality (Turner et al. 1966), and disease (Duriscoe and Graban 1992) in the lifecycle of the saguaro. Long-term monitoring in Saguaro National Park (SNP) began when an unidentified bacterial disease was posited as the cause of saguaro mortality observed in the late 1930s (McAuliffe 1993). Gill and Lightle (1942) conducted a study of a one-mile square section in the northwest corner of the Rincon Mountain District known as “Section 17”. Saguaro exhibiting symptoms of the disease were removed in the southern half of the section, and the northern half was used as a control group. A comprehensive saguaro census of Section 17 was taken in 1941. Six ten-acre subplots were monitored annually ever since, creating a continuous 75-year record of saguaro population dynamics. Analysis of this record shows the crucial relationship of nurse trees in saguaro recruitment and the role of catastrophic freezing events in saguaro mortality (Orum et al. 2016). The entire square mile area of Section 17 was resurveyed by a team of volunteers and park staff in 2011-2012 (Conver et al. 2017). This census found a total of 9023 saguaros in 2011-2012, while the census performed by Gill and Lightle (1942) had found 13,304 in 1941, a decrease of 31.4%. This comparison yielded important insight into the changing demography of the population. The population in 2011 was shown to be more skewed toward younger, smaller saguaros, whereas the 1941 population was dominated by mature, tall saguaros with fewer young individuals.

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. The Section 17

censuses collected by Gill and Lightle (1942) and again by Conner et al. (2017) 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 like these are unlikely to be regularly repeated. While these one square-mile census efforts represent the largest saguaro census efforts in terms of area, they still comprise less than 1% of the total area of SNP.

The availability of fine spatial resolution (15.24 cm) aerial imagery of SNP enables the possibility of using remote sensing to map saguaros quickly over large areas. Although the signature of an individual saguaro from nadir viewing may only be 2-3 pixels at this resolution, the shadows cast by saguaros tend to be much more easily identifiable as long, linear areas of dramatic contrast (Figure 1). Fortunately, the saguaro is relatively unique in its shape and height in the Arizona Upland subdivision of the Sonoran Desert (Shreve 1910). This enables the use of unique shadow signatures as proxies for saguaro locations.

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. (2011) presented a method of measuring the heights of buildings in satellite imagery by analyzing neighboring areas of high reflectance contrast. Shettigara and Sumerling (1998) employed tree heights and shadows as calibration data to estimate building heights based on building shadows. This research uses a somewhat similar approach of using a ratio of shadow and non-shadow regions to score pixels based on the likelihood of being within a saguaro shadow. The shadow method differs from Comber et al. (2012) and Shettigara and Sumerling (1998) in that this research attempted to detect feature presence, not estimate feature height. In addition, the aerial imagery used in this research contains a range of acquisition dates and times, while Comber et al. (2012) and

Shettigara and Sumerling (1998) 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.

The use of aerial imagery for mapping saguaros was performed in a limited extent by Gill and Lightle (1942). Visual inspection of aerial imagery was performed to map saguaro locations in Section 17. However, these methods relied on labor intensive visual interpretation, and the results were not validated by field measurements. Remote sensing has been applied for mapping other vegetation in the Sonoran Desert. Sankey et al. (2015) used ground-based LiDAR to monitor vegetation dynamics and canopies but ignored the saguaros due to sparse cover in the study area. Drake (1994) used visual interpretations of videography to identify vegetation communities. While saguaros were useful in the identification of “paloverde-saguaro communities”, no attempt was made to map individual saguaros. In subsequent research, Drake (2000) did use visual interpretation to identify individual saguaros in individual frames of videography of the San Pedro River watershed, located to the east of RMD. Five hundred fifty-four small areas within the large study area for analysis were sampled for analysis, but a complete census was not attempted. Although a complete census could be conducted visually using Drake’s videography, it would involve a prohibitive amount of analyst labor.

Wallace et al. (2016) mapped invasive buffelgrass locations and phenology in SNP using Normalized Difference Vegetation Index (NDVI) patterns in MODIS satellite data. Similar 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 32cm, 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. This research utilized Pima Association of Governments (PAG) aerial imagery of SNP because it is the finest spatial resolution (15.24cm) imagery currently available and therefore presents the best opportunity for reliable remote sensing of saguaros.

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 by 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 could yield insight into the variables that affect saguaro population dynamics. Large censuses undertaken years apart could produce population change data that would be useful for pinpointing areas of growth or decline for further study.

The primary objectives of this research were to:

1. Develop a reliable methodology and useful tool for automatic saguaro location detection in digital aerial imagery that land managers can easily apply to large areas.
2. Use the tool to conduct a saguaro census of SNP.
3. Validate the resulting point locations against contemporary *in situ* field measurements.
4. Investigate sources of error inherent in the use of shadows as proxies for saguaro locations.
5. Estimate the mature saguaro density distribution, and the total saguaro population in SNP by correlating remotely sensed saguaro locations with field plot observations.

## 2. STUDY AREA

This research focused on saguaro detection within the boundaries of Saguaro National Park. The park is divided into two districts: Tucson Mountain District (TMD), located to the northwest of the city of Tucson, and Rincon Mountain District (RMD), located adjacent to Tucson on the east side (Figure 2). Most of the lower elevation areas in the park are classified as Sonoran desertscrub, including Arizona Upland and Plains of Sonora subdivisions (Shreve and Wiggins 1964). Sonoran desertscrub hosts a variety of cacti besides the saguaro, including several types of cholla (*Cylindropuntia*), barrel cactus (*Echinocactus*, *Ferocactus*), pincushion cactus (*Mammillaria*, *Escobaria*), and organ pipe cactus (*Stenocereus thurberi*) (Brown 1994). 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*) (Brown 1994). Geologically, SNP is contained within the Basin and Range Physiographic Province (Powell et al. 2006). 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 30-35cm and follows bi-modal wet and dry periods with rainfall peaks in the winter and in the summer monsoon period (Funicelli et al. 2000).

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 (Powell et al. 2006). Although the shadow detection methodology was applied to the high elevation regions in RMD, saguaro locations at elevations greater than 1550m were deleted. The maximum elevation threshold for saguaros has been established as 1500m (USDA-NRCS 2018). An elevation limit of 1550m 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. DATA**

#### **3.1. Pima Association of Governments Aerial Imagery**

The Pima Association of Governments (PAG) has compiled fine spatial resolution digital aerial imagery of most of Pima County, including SNP. This research used most recent 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 2-5 pixels at this resolution, the shadows cast by the saguaros tend to be much more easily identifiable due to the long horizontal signature (Figure 1). These signatures enabled a large extent saguaro census to be performed on Saguaro National Park using PAG's remotely sensed data. The PAG imagery is made freely available to University of Arizona students and staff through the University of Arizona Library.

#### **3.2. PAG Imagery Time of Acquisition Point Data**

PAG also provided point location data that contained information regarding the date and time of acquisition of the raw imagery. The data from these points were used to calculate the solar azimuth angle for various acquisition times, which was critical to the implementation of the shadow methodology.

#### **3.3. Public Land Survey System and Saguaro National Park Polygon Geometry**

A Public Land Survey System (PLSS) polygon geometry was obtained from ESRI Online. The PAG imagery is divided into sections based on the PLSS, with each TIF file being

focused on a section with overlap in between neighboring PLSS sections. This research used the PLSS polygon to clip the imagery to PLSS sections, each approximately one square mile in area, to avoid duplicate scanning of overlapping regions.

Polygon geometry data of the boundaries of SNP was obtained from the Integrated Resource Management Applications (IRMA) online portal of the National Park Service (NPS). Because SNP contains many partial PLSS sections, it was necessary to scan these PLSS sections in their entirety and then clip the saguaro location points that fell outside of the boundaries of SNP.

### **3.4. USGS Digital Elevation Model**

A digital elevation model (DEM) was obtained from USGS's National Elevation Dataset (NED). This raster dataset provided elevation in meters at spatial resolution of 1/3 arcsecond, about 10 meters. This data was used to eliminate saguaro location points above 1550 meters in elevation. These points were false positives caused by other vegetation and rocky areas and were automatically deleted because they exceeded the maximum elevation threshold of saguaros in SNP.

### **3.5. Saguaro Location Data Collected in 2010**

Saguaro location data collected in 2010 by SNP staff in 11 plots were used to validate the results of the shadow method census. These plot locations were established in 1988 as part of a large network of long-term monitoring plots (Duriscoe and Graban 1992). The 2010 resurvey included highly accurate geolocation of saguaro locations, as well as height measurements. Between the 11 plots, 2556 saguaros were recorded. 1053 of these had a height of 1.5 meters or greater.

### **3.6. Saguaro Locations from Section 17 Census Collected in 2011-2012**

Georeferenced saguaro locations and height data from the Conver et al. (2017) 2011-2012 census were obtained from the NPS IRMA data portal. A set of 100 survey individuals were matched with individuals from the shadow method results to establish a minimum height threshold for the shadow methodology. This dataset was not used for validation due to frequent georeferencing and location uncertainties that precluded one-to-one validation techniques. This data set was divided into 256 hectare plots as the basis for a regional comparison between densities found by Conver et al. (2017) census and those found by the shadow method.

### **3.7. Data Collected During Field Investigation of Missing Saguaros**

We conducted fieldwork in two of the 11 SNP plots to locate “missing” saguaros that failed to produce a shadow signature in the multispectral aerial imagery. We located 41 out of the 44 “missing” saguaros in two plots. The area surrounding of each of the 41 saguaros located was evaluated for the presence of landscape characteristics that could preclude or obscure a shadow signature in the imagery.

## **4. METHODS**

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. An overview of the method is provided in Figure 3. 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 30-75 cm, which comprise 2-5 pixels in the multispectral imagery (USDA NRCS 2018). 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 approximately two pixels (Figure 1) that contrast sharply with surrounding non-shadow areas.

The length of the shadow depends on solar zenith angle, saguaro height, and local topography. The shadow methodology 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 non-saguaro shadows, custom search kernels were utilized to ratio shadow regions against adjacent non-shadow 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. Both approaches failed to yield satisfactory initial results. The novel 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 illustrated in Figure 3.

Although the PAG imagery contains four bands, only the red band was used by the shadow method. Overall, the digital numbers of all four bands were found to be highly correlated to each other (Table 5). In Section 17, the band combination with the lowest correlation was between band 3 and band 4, which was 95%. All other band combinations showed correlations greater than 95%. The red band was found to offer the highest contrast between shadow regions and non-shadow regions and was therefore selected as the basis of the shadow methodology.

#### **4.1. 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 (Figure 3-B) was acquired over the span of ten days in late April 2011. The

images were taken at various times of day with consequently various solar azimuth angles and corresponding shadow directions. The flight data points (Figure 3-A) containing information about the date and time of the raw image acquisition were used to calculate solar azimuth angles (Figure 3-E). This was done using the PySolar Python library developed by Brandon Stafford and collaborators (Figure 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  $70^\circ$ , corresponding to imagery taken at 12:30PM local time on April 21, 2011. The minimum solar elevation angle was  $31^\circ$ , corresponding to imagery taken at 8:21AM 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  $70^\circ$  the shadows of short saguaros became increasingly small, making them difficult to separate from ancillary shadows in the image. However, this effect is partially offset by increased contrast between shadow and non-shadow regions caused by direct solar insolation at high solar elevation angles.

## **4.2. Calculation of Per Pixel Shadow Value**

The digital aerial imagery was first clipped to square-mile sections based on the PLSS polygon geometries. A list of solar azimuth angles was then determined from the location of flight data points 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 square-mile section in a matter of seconds and took several images. However, some of the imagery 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 greater than 10 degrees different from the previous scan.

A saguaro shadow ratio (Figure 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 (Figure 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 are can be adjusted based on the spatial resolution of the imagery. The search kernels were 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 non-shadow search kernels were defined as two rectangles identical to the shadow kernel and located directly parallel and adjacent to the shadow file on either side (Figure 4).

These custom search kernels (Figure 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 non-shadow region would have a relatively high mean of digital numbers. A ratio of the three regions (Figure 3-H) was calculated by dividing the sum of the mean of the non-shadow regions by the mean of the shadow region (Figure 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 five or greater was ideal for identifying the highest proportion of saguaro shadow signatures while limiting false positives due to non-saguaro shadows in the scene. Pixels with a score below five were discarded.

#### **4.3. Using Pixels Scores to Locate the Saguaro Base**

Pixels assigned a shadow ratio score of five or greater were then grouped into contiguous regions (Figure 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 less than  $180^\circ$  and the southeastern most pixel when the solar azimuth angle was greater than  $180^\circ$  (Figure 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 (Figure 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 (Figure 3-L) to delete duplicate points that occurred within a common shadow region (Figure 3-N). To create the shadow mask, 30 locations were identified in Section 17 (Figure 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 (Figure 3-I).

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

The remaining pixels were converted into point locations (Figure 3-P). The point locations were assigned an elevation value based on the USGS DEM. Points above 1550 meters were deleted, as 1500 meters has been shown to be the maximum elevation at which saguaros have been observed (USDA NRCS 2018). 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. The number of saguaros in each hectare cell is shown by a pseudo-color gradient scheme (Figure 5, 6).

#### **4.4. 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. (2017) 2011-2012 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. (2017) 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. (2017) survey that were between 1 and 2 meters tall. From this subset, we identified 100 locations where the shadow method agreed with the Conver et al. (2017) survey data. We then recorded the minimum height as recorded by Conver et al. (2017) from these 100 matching locations. The minimum height identified was 1.5 meters. 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 meter saguaros varied with solar elevation angle and local topography.

#### 4.5. Accuracy Assessment

Eleven *in situ* field surveys plots collected by SNP staff in 2010 (Figure 2) were used to assess the accuracy of the shadow detection method. These data included the heights and locations in 11 plots, five in the Rincon Mountain District and six in the Tucson Mountain District. The plots varied in size from 0.8 hectares to 1.9 hectares. Saguaros with a height of less than 1.5 meters were discarded. Saguaros with neighbors less than 1.5 meters away were discarded to minimize errors due to proximate saguaros not producing sufficiently distinct shadows for reliable detection. We considered 1.5 meters 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 were compared to the shadow method points and classified as correct (Figure 10A) 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 (Figure 10B).
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 (Figure 10C).
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 (Figure 10D).

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 (Figure 10E).

#### **4.6. 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, two 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 of 2017 (Figure 2).

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. 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 saguaros 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.

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.

#### 4.7. Estimating Total Saguaro Density and Population

The relationship between the results of the shadow method and the results of field surveys in the 11 SNP was used to estimate densities and total populations of saguaros in SNP. Although the 11 plots cover a relatively small area (17.9 hectares), the locations of the plots are spatially distributed across both districts and varied landscapes of SNP. The plot locations were established in 1983 as “representative habitats” and were not located based on random sampling (Swann et al. 2018). However, the saguaro location data from these plots serve the purposes of this research, as the saguaros populations in the plots vary in density and demography. Although the plots do not represent the diversity of landscapes and saguaro populations in SNP completely, these locations provided a representative sample from which estimates can be made.

To estimate saguaro densities and populations from the shadow method’s results, omission and commission biases were factor in using linear regression. Estimates of saguaro density per hectare in each district were calculated by applying a linear regression equation to the shadow method’s per hectare density results. Hectares with zero detected saguaros were excluded in the calculation of per hectare densities. 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 product of standard deviations was calculated when the shadow method’s per hectare densities were multiplied by the regression coefficient. The resulting standard deviation ( $\sigma$ ) was found by using the mean ( $\mu_1$ ) and standard deviation ( $\sigma_1$ ) of the shadow method’s results per hectare and the mean ( $\mu_2$ ) and standard deviation ( $\sigma_2$ ) of the regression coefficient as input to Equation 1.

$$\sigma = \sqrt{\sigma_1^2 * \sigma_2^2 + \sigma_1^2 * \mu_2^2 + \sigma_2^2 * \mu_1^2} \quad (1)$$

**Equation 1.** Standard deviation of the product of two variables with known variances

Estimates of total saguaro populations (mature and immature) were also calculated using linear regression. The number of mature saguaros per hectare in the 11 SNP plots were regressed against the total number of saguaros in those plots. The resulting linear regression equation was applied to mature saguaro estimates to produce total saguaro estimates. Equation 1 was used to calculate the standard deviation of the total saguaro population, given the mean ( $\mu_1$ ) and standard deviation ( $\sigma_1$ ) of the mature saguaro estimate and the mean ( $\mu_2$ ) and standard deviation ( $\sigma_2$ ) of the total saguaro regression coefficient.

## 5. RESULTS AND DISCUSSION

### 5.1. Saguaro Density and Distribution

Our automated saguaro survey of SNP detected 446,092 saguaro shadows across 89.5 square miles (23,180 hectares) of SNP. Densities ranged from 0 per hectare 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 3,726 hectares, equal to 15% of the total area. Histograms of per hectare densities in each district show a more positive skew in RMD than in TMD (Figures 7, 8).

The saguaro density maps produced from this automated survey (Figure 5, 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 Tucson Mountain District 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.

## **5.2. 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. The 455 (42%) saguaros that were not correctly identified were divided into three categories: no shadow signature (not identifiable by a human analyst), weak shadow signature (possibly identifiable by human analyst), and strong shadow signature (distinctly identifiable by a human analyst). During the accuracy assessment, 235 (21%) were classified as no signature, 140 (13%) were classified as weak signature, and 80 (7%) were 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 had the highest omission rate at 61% (Figure 9). 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 non-saguaro shadows in the imagery. Strong signature omissions are the most likely to be corrected by shadow method refinements, which are discussed in Section 5.8.

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 lots, 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 five when selecting pixels based 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.

### **5.3. Fieldwork to Identify Missing Saguaros**

During our fieldwork to investigate saguaro shadow omission from aerial imagery, 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%). Results are shown in Table 3.

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” (Steenburgh and Lowe 1969). 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.

#### **5.4. 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 0.966) is present between the shadow method results and the mature saguaro field survey data (Figure 11). This comparison was used to calculate the linear regression equation (Table 4B) used to adjust saguaro method results to predict mature saguaro counts. Although the Conner et al. (2017) Section 17 saguaro location data were not sufficiently spatially accurate for individual saguaro validation, the dataset was useful to illustrate the relationship between the shadow method’s results and field survey data. Section 17 was divided into 256 hectare squares to compare the Conner et al. (2017) saguaro count to the result of the shadow method. This comparison as well as the 11 SNP plot comparison is shown in Figure 11. The shadow method’s results show a similar linear relationship to both field survey datasets. The Conner et al. (2017) data show a higher deviation from the trendline, likely due in part to lower spatial accuracy of the point data.

The total population (mature and immature) is compared with the shadow method’s results in Figure 12. The coefficient of determination ( $R^2$ ) value of the shadow results compared with total saguaro count was 0.662. This decrease in correlation as compared to mature saguaro

correlation is due to the inability of the shadow method to detect variability in immature saguaros. Field survey data of mature saguaros and total saguaros are compared in Figure 13. This comparison was used to determine the linear regression equation (Table 4B) for adjusting mature saguaro estimates to predict total saguaro counts.

Predicted mature saguaros (adjusted for omission and commission errors using linear regression) compared with mature saguaros and with total saguaros in field survey data are shown in Figures 14 and 15 respectively. The strength of the linear correlation between the shadow method and mature saguaros in the field results is shown by the proximity of the data point to the identity line in Figure 14. Figure 15 illustrates the high degree of variability in the populations of immature saguaros in the 11 plots. Predicted total saguaros (predicted mature saguaros adjusted for total population using linear regression) compared to total saguaros in the field survey data are shown in Figure 16, illustrating the uncertainty of predicting total population using results from the shadow method.

## **5.5. Estimates of Total Density and Total Population**

We compared the shadow method's estimates of total saguaro density per hectare against similar estimates made by Funicelli et al. (2000). The regression equations (Table 4B) were used to calculate per hectare and overall estimates for saguaro density in SNP (Table 4A). We estimated a density of 132 saguaros per hectare in TMD and 103 saguaros per hectare in RMD. Funicelli et al. (2000) estimated these densities as 127 and 64, respectively. Our estimate of total saguaro population in SNP was 2,284,623. Funicelli et al. (2000) estimated the total population in 2000 to be 1,624,857.

The Funicelli et al. (2000) research was based on extrapolation of data measured in 18 small monitoring plots. Their research was conducted 11 years prior to the acquisition date of our

imagery. They reported an increase of 32% in the saguaro population over the previous ten years, based on a comparison between populations in 1990 and 2000. If the mature saguaro population in SNP continued that trend between 2000 and 2011 and their methodology had been applied in 2011, the results would likely have been close to the estimates reported in this study. Although this research used a substantially different method to estimate saguaro populations in SNP, the estimates produced were comparable to those of Funicelli et al. (2000).

### **5.6. Areas of Low Accuracy**

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 novel shadow method showed signatures that were much shorter in length than in other images. The imagery for this region was acquired at 12:44PM on April 21, 2011, with a calculated solar elevation angle of 68 degrees. If the time of acquisition is close to local noon (12:27PM), 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<sup>st</sup>), or at lower latitudes. Plot 7 is 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.

### **5.7. Strengths of the Shadow Detection Method**

The primary strength of the shadow detection method is the ability to scan large areas

quickly with a lesser amount of labor than visual analysis. This method produced a mature saguaro density map of SNP for the first time. It also enabled a much more comprehensive estimation of the total mature saguaro count in the park than was previously possible. The shadow method was developed to be fully automated so that resource managers and researchers can easily apply it to new imagery. Parameters specifying the length and width of the custom search kernel can be easily adapted to accommodate imagery with different spatial resolutions. If new imagery is obtained, the shadow detection method will facilitate change detection analysis. An analyst will certainly be able to identify areas that have experienced net saguaro gain or loss compared to past imagery. If new imagery is produced at a regular interval, the shadow detection method can be used to create a spatially explicit saguaro density and population time series maps of the entire park. This will be a valuable tool in the study of saguaro population dynamics, including analysis of the effects of invasive species, wildfire, and land management practices.

### **5.8. Weaknesses of the Shadow Detection Method**

Compared to traditional field studies of saguaros, the image-based shadow detection method does not produce a comprehensive survey of all the saguaros in a population. In the 11 plots used for validation, 1,345 of the 2,556 (52.6%) saguaros were less than 1.5 meters tall. These shorter saguaros are much more difficult for any remote sensing method to capture in their entirety. Of the population of saguaros above 1.5 meters in height, 21% failed to produce a shadow signature in the aerial images. Relying on shadows as proxies instead of direct measurement of saguaros will inherently produce this type of error to various degrees. Optimal daytime image acquisitions and higher spatial resolution imagery would be useful in reducing this error, but such imagery does not currently exist and would be prohibitively expensive to commission. Ancillary data, such as LiDAR or structure from motion (SFM) photography would

enable multiple sensor data analysis and potentially reduce uncertainty in results.

## **5.9. Opportunities for Method Refinement**

### **5.9.1 Dynamic lengths of custom kernels based on solar elevation**

Because the aerial imagery was acquired at different times during the day, the length of the shadows produced by the saguaros varies in accordance with the solar elevation angle. The current method incorporates the solar azimuth angle but does not incorporate the solar elevation angle. If the shadow method was responsive to solar elevation, it could search for shorter shadows when acquisition times are closer to noon, and longer shadows when acquisition times are closer to sunrise or sunset. This could augment short saguaro detection for images acquired at extreme solar elevation angles. However, a method that is able to detect short saguaros at high solar elevation angles may suffer higher rates of commission, as short signatures are more difficult to differentiate from non-saguaro (e.g. rocks, trees, and shrubs) shadows.

### **5.9.2. Dynamic widths of custom kernels**

The shadow methodology used a fixed custom kernel width of 2 pixels. This corresponds to a ground distance of 30.48cm in the imagery. This measurement approximates the average saguaro shadow width, which is controlled by saguaro diameter. Although this can be used as a reasonable estimate of average saguaro diameter, it does not account for variability in diameter within the saguaro population. One solution may be to calculate shadow scores for ten possible widths between 1.5 pixels and 2.5 pixels. The width with the highest scoring shadow ratio score for each location could be used. This method would better account for variability in saguaro diameter, which could successfully identify some of the saguaros missed by the current method. However, employing this method would dramatically increase processing time and may introduce additional commission error.

### **5.9.3. Variable shadow masking**

The current method uses a fixed value of 70 as the digital number of the red band to create the shadow mask. All pixels with red band digital numbers less than 70 are considered to be shadow. However, because the images vary in terms of time of day, soil reflectance, and angular resolution, a static value for shadow classification is not ideal. A properly calibrated sensor and calculated reflectance values would enable a more exact shadow threshold to be established. This technique could produce a more accurate shadow mask, which may be able to correctly identify some of the saguaros that have weak or overlapping shadow signatures (e.g. with dark soils, detritus, or trees).

### **5.10. Automation vs. 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 (Russakovsky et al. 2015). However, analyzing large areas like 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 seeks to be sufficiently accessible and inexpensive so that land managers can implement it on future imagery and in other areas within the saguaro's range.

## **6. 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 based on the ratio of adjacent shadow and non-shadow regions. The results of this methodology were compared to *in situ* field survey data collected by SNP to assess accuracy. 21% of the saguaros found in the field surveys produced no shadow signature in the aerial images. 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 59% of saguaros taller than 1.5 meters. 21% produced no shadow signature. 13% produced a weak shadow signature that the shadow method did not detect, and 7% produced a strong signature which the shadow method did not detect. Several possible refinements of the methodology were discussed, which could improve the accuracy of the results when compared against *in situ* field surveys.

The shadow methodology presents several opportunities for further study:

1.     **Application in other areas.** Although our study area was limited to the boundaries of Saguaro National Park, 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 (Rodriguez-Buritica et al. 2013), could use the shadow methodology to supplement ongoing studies.
2.     **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.

3.     **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 shadow method provides a valuable tool for SNP resource managers and other researchers and stakeholders to conduct large extent saguaro censuses with a minimum 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.

## **ACKNOWLEDGEMENTS**

Aerial multispectral imagery and flight data were provided by Pima Association of Governments. Pysolar software was provided by Brandon Stafford and collaborators. 2011-2012 Section 17 saguaro survey data, 2010 saguaro survey data, and a National Park boundaries polygon geometry were provided by the National Park Service via the Integrated Resource Management Applications (IRMA) online portal. The University of Arizona Peace Corps Coverdell Fellows program funded Forest Carter's assistantship with Saguaro National Park.

## REFERENCES CITED

- Archer, S. and Predick, K. (2008). Climate Change and Ecosystems of the Southwestern United States. *Rangelands*, 30(3), 23-28. Retrieved from <http://www.jstor.org/stable/25145389>
- Brown, D. E. (1994) Biotic communities: Southwestern United States and Northwestern Mexico. Salt Lake City: University of Utah Press.
- Bruhn, J. G. (1971) *Carnegiea gigantea*: The saguaro and its uses. *Economic Botany*, 25(3), 320-329.
- Comber, A., Umezaki, M., Zhou, R., Ding, Y., Li, Y., Fu, H., Tewkesbury, A. (2012) Using shadows in high-resolution imagery to determine building height. *Remote Sensing Letters*, 3(7), 551-556.
- Conver, J. L., Foley, T., Winkler, D. E., and Swann, D. E. (2017) Demographic changes over 70 years in a population of saguaro cacti (*Carnegiea gigantea*) in the northern Sonoran Desert. *Journal of Arid Environments*, 139, 41–48.  
<https://doi.org/http://dx.doi.org/10.1016/j.jaridenv.2016.12.008>
- Drake, S. E. (1994) Visual interpretation of vegetation classes from airborne videography: An evaluation of observer proficiency with minimal training (MS). Tucson, Arizona: University of Arizona, 1994.
- Drake, S. E. (2000) Climate-Correlative Modeling of Phytogeography at the Watershed Scale (PhD.) Tucson, Arizona: University of Arizona, 2000.
- Drezner, T. D. (2003) Saguaro (*Carnegiea gigantea*, *Cactaceae*) Age-Height Relationships and Growth: The Development of a General Growth Curve. *American Journal of Botany*, 90(6), 911-914. Retrieved from <http://www.jstor.org/stable/4124085>
- Drezner, T. D. and Lazarus, B. L. (2008) The Population Dynamics of Columnar and Other Cacti: A Review. *Geography Compass*, 2: 1–29. doi:10.1111/j.1749-8198.2007.00083.x
- Drezner, T. D. (2014) The keystone saguaro (*Carnegiea gigantea*, *Cactaceae*): A review of its ecology, associations, reproduction, limits, and demographics. *Plant Ecology*, 215(6), 581-595.
- Duriscoe, D. M. and Graban, S. L. (1992) Epidermal browning and population dynamics of giant saguaros in long-term monitoring plots. Proceedings of the Symposium on Research in Saguaro National Monument, 23-24 January 1991. Southwest Parks and Monuments Association, Globe, Arizona.

- Funicelli, C. S., Anning, P. J., and Turner, D. S. (2000) Long-term vegetation monitoring at saguaro national park: A decade of change. Tucson, Arizona: United States Geological Survey, Western Ecological Research Center, Sonoran Desert Field Station and School of Renewable Natural Resources, University of Arizona.
- Gill, L.S. and Lightle, P.C. (1942) Cactus disease investigations: an outline of objectives, plans, and accomplishments on project j-2-8. Report to the Bureau of Plant Industry. In: Steenbergh, W.F., Lowe, C.H. (Eds.), *Ecology of the Saguaro III. Growth and Demography*. Scientific Monograph Series. Number 17, vol. 1983. National Park Service, Washington DC.
- McAuliffe, J. R. (1993) Case Study of Research, Monitoring, and Management Programs Associated with the Saguaro Cactus (*Carnegiea Gigantea*) at Saguaro National Monument, Arizona. National Park Service, Cooperative National Park Resources Studies Unit, School of Renewable Natural Resources, The University of Arizona.
- Niering, W., Whittaker, R., and Lowe, C. (1963) The Saguaro: A Population in Relation to Environment. *Science*, 142(3588), 15-23. Retrieved from <http://www.jstor.org.ezproxy3.library.arizona.edu/stable/1711856>
- Orum, T. V., Ferguson, N., and Mihail, J. D. (2016) Saguaro (*Carnegiea gigantea*) Mortality and population regeneration in the cactus forest of Saguaro National Park: seventy-five years and counting. *PLOS ONE*, 11(8), 1–21. <https://doi.org/10.1371/journal.pone.0160899>
- Pierson, E. A., Turner, R. M., and Betancourt, J. L. (2013) Regional demographic trends from long-term studies of saguaro (*Carnegiea gigantea*) across the northern Sonoran Desert. *Journal of Arid Environments*, 88, 57-69.
- Powell, B. F., Halvorson, W. L., and Schmidt, C. A. (2006) Vascular plant and vertebrate inventory of Saguaro National Park, Rincon Mountain District. OFR 2006-1075. U.S. Geological Survey, Southwest Biological Science Center, Sonoran Desert Research Station, University of Arizona, Tucson, Arizona, (November).
- Rodriguez-Buritica, S., Raichle, H., Birt, T., Webb, R., Turner, R., Pierson, E., and Venable, D. (2013) Population dynamics of Sonoran Desert saguaro cactus (*Carnegiea gigantea*) at the Desert Laboratory (Tucson, Arizona): "Ecological Archives" E094-151. *Ecology*, 94(7), 1660-1660. Retrieved from: <http://www.jstor.org/stable/23596956>
- Russakovsky, O., Deng, J., Su, H., Krause, J., Satheesh, S., Ma, S., and Fei-Fei, L. (2015) ImageNet Large Scale Visual Recognition Challenge. *International Journal of Computer Vision*, 115(3), 211–252. <https://doi.org/10.1007/s11263-015-0816-y>

- Sankey, J. B., Munson, S. M., Webb, R. H., Wallace, C. S. A., and Duran, C. M. (2015) Remote sensing of Sonoran Desert vegetation structure and phenology with ground-based LiDAR. *Remote Sensing*, 7(1), 342–359. <https://doi.org/10.3390/rs70100342>
- Shettigara, V. K., and Sumerling, G. M. (1998). Height determination of extended objects using shadows in SPOT images. *Photogrammetric Engineering and Remote Sensing*, 64(1), 35–44.
- Shreve, F. (1910) The rate of establishment of the giant cactus. *The Plant World*, 13(10), 235–240. Retrieved from: <http://www.jstor.org/stable/43476815>
- Shreve, F. and Wiggins, I. L. (1964) Vegetation and flora of the Sonoran Desert. Stanford University Press. Retrieved from <https://books.google.com/books?id=jyMmAQAAMAAJ>
- Steenbergh, W. and Lowe, C. (1969) Critical Factors During the First Years of Life of the Saguaro at Saguaro National Monument, Arizona. *Ecology*, 50(5), 825–834. doi:10.2307/1933696
- Steenbergh, W., and Lowe, C. (1977) Ecology of the saguaro: II, Reproduction, germination, establishment, growth, and survival of the young plant. Washington D.C. Dept. of the Interior, National Park Service.
- Swann, D., Conver, J., Winkler, D., and Harper, C. (2018) Climate Change and the Saguaro Cactus. Unpublished technical report.
- Turner, R. M., Alcorn, S. M., Olin, G., and Booth, J. A. (1966) The influence of shade, soil, and water on saguaro seedling establishment. *Botanical Gazette*, 127(2/3), 95–102. 10.1086/336348.
- USDA-NRCS. (2018) United States Department of Agriculture, National Resource Conservation Service. 2017. The PLANTS database. Available at: <http://plants.usda.gov>. Accessed 27 January 2018.
- Wallace, C., Walker, J., Skirvin, S., Patrick-Birdwell, C., Weltzin, J., and Raichle, H. (2016) Mapping presence and predicting phenological status of invasive buffelgrass in southern Arizona using MODIS, climate, and citizen science observation data. *Remote Sensing*, 8(7), 524.

## TABLES

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 -<br>No signature | Saguaros omitted -<br>Weak signature | Saguaros omitted -<br>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                |

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                  |

Table 3. Results of fieldwork to identify saguaros that failed to produce shadow signatures. Each location was visited *in situ* and analyzed for factors that could preclude a shadow signature appearing in the aerial imagery. Vegetation interference was found to be a factor in 61% of cases, and rocky slopes in 54% of cases, and shadow alignment in 20% of cases. 3 saguaros were not located.

| Saguaro ID | Site 6                       | Site 8                  |
|------------|------------------------------|-------------------------|
| 0          | Vegetation                   | Shadow Alignment        |
| 1          | Not Located                  | Shadow Alignment        |
| 2          | Vegetation, Rocky Slope      | Vegetation              |
| 3          | Vegetation                   | Rocky Slope             |
| 4          | Vegetation, Shadow Alignment | Shadow Alignment        |
| 5          | Shadow Alignment             | Vegetation              |
| 6          | Not Located                  | Vegetation              |
| 7          | Vegetation, Shadow Alignment | Rocky Slope             |
| 8          | Vegetation, Shadow Alignment | Vegetation              |
| 9          | Vegetation, Rocky Slope      | Shadow Alignment        |
| 10         | Vegetation                   | Rocky Slope             |
| 11         | Vegetation, Rocky Slope      | Rocky Slope             |
| 12         | Vegetation, Rocky Slope      | Vegetation              |
| 13         | Vegetation, Rocky Slope      | Rocky Slope             |
| 14         | Rocky Slope                  | Vegetation, Rocky Slope |
| 15         | Vegetation, Rocky Slope      | Not Located             |
| 16         | Vegetation                   | Rocky Slope             |
| 17         | Vegetation, Rocky Slope      | Rocky Slope             |
| 18         | Vegetation, Rocky Slope      | Rocky Slope             |
| 19         | Vegetation, Rocky Slope      |                         |
| 20         | Vegetation                   |                         |
| 21         | Vegetation                   |                         |
| 22         | Vegetation, Rocky Slope      |                         |
| 23         | Rocky Slope                  |                         |
| 24         | Rocky Slope                  |                         |

Table 4A. Density and cumulative estimations of saguaros in Saguaro National Park. Linear regression equations (Table 4B) were used to estimate mature and total populations. Standard deviations for the results of the linear regressions were calculated using Equation 1. Per hectare densities exclude hectares with 0 saguaros.

|                         |            | Detected by<br>Shadow Method | Estimated<br>Mature | Estimated Total<br>Population<br>(Mature and<br>Immature) |
|-------------------------|------------|------------------------------|---------------------|-----------------------------------------------------------|
| Hectare Density<br>RMD  | Mean       | 14.40                        | 26.45               | 102.63                                                    |
|                         | Std. Dev.  | 18.57                        | 30.41               | 69.17                                                     |
| Hectare<br>Density TMD  | Mean       | 31.77                        | 50.88               | 131.97                                                    |
|                         | Std. Dev.  | 24.11                        | 38.66               | 83.60                                                     |
| SNP Cumulative<br>Count | Sum        | 446,092                      | 748,626             | 2,284,623                                                 |
|                         | Std. Error | NA                           | 75,260              | 200,009                                                   |

Table 4B. Linear regression terms used to calculate saguaro estimations (Table 4A). The omission and commission regression was calculated by applying linear regression to shadow method results and field survey results in 11 spatially distributed SNP plots. The total population regression was calculated by applying linear regression to mature and total population counts in field survey results in 11 plots.

|           | Omission and Commission Regression |           | Total Population Regression |           |
|-----------|------------------------------------|-----------|-----------------------------|-----------|
|           | Coefficient                        | Intercept | Coefficient                 | Intercept |
| Mean      | 1.407                              | 6.189     | 1.2007                      | 70.872    |
| Std. Dev. | 0.313                              | 13.711    | 0.750                       | 50.838    |

Table 5. Correlation matrix of four bands of the digital aerial imagery of Section 17. Because the bands were highly correlated with each other, only the red band was used in the shadow method, as it provided the highest contrast between shadow and non-shadow regions.

| Band        | 1 (Red) | 2 (Green) | 3 (Blue) | 4 (Infrared) |
|-------------|---------|-----------|----------|--------------|
| 1           | 1.00    | 0.99      | 0.98     | 0.97         |
| 2(Green)    | 0.99    | 1.00      | 0.99     | 0.97         |
| 3(Blue)     | 0.98    | 0.99      | 1.00     | 0.95         |
| 4(Infrared) | 0.97    | 0.97      | 0.95     | 1.00         |

## FIGURES

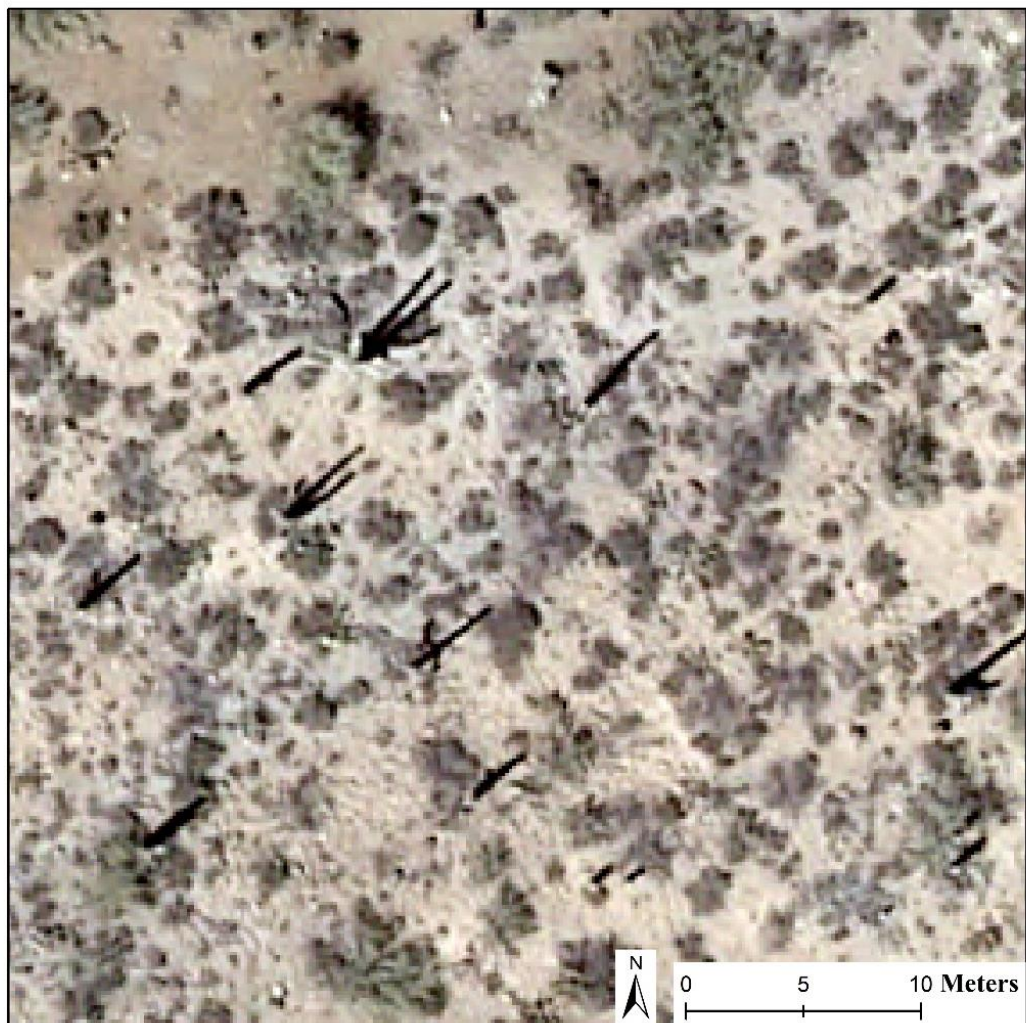


Figure 1. Sample of natural color multispectral imagery in the Tucson Mountain District of Saguaro National Park. Long, linear shadow signatures are indicative of saguaro locations.

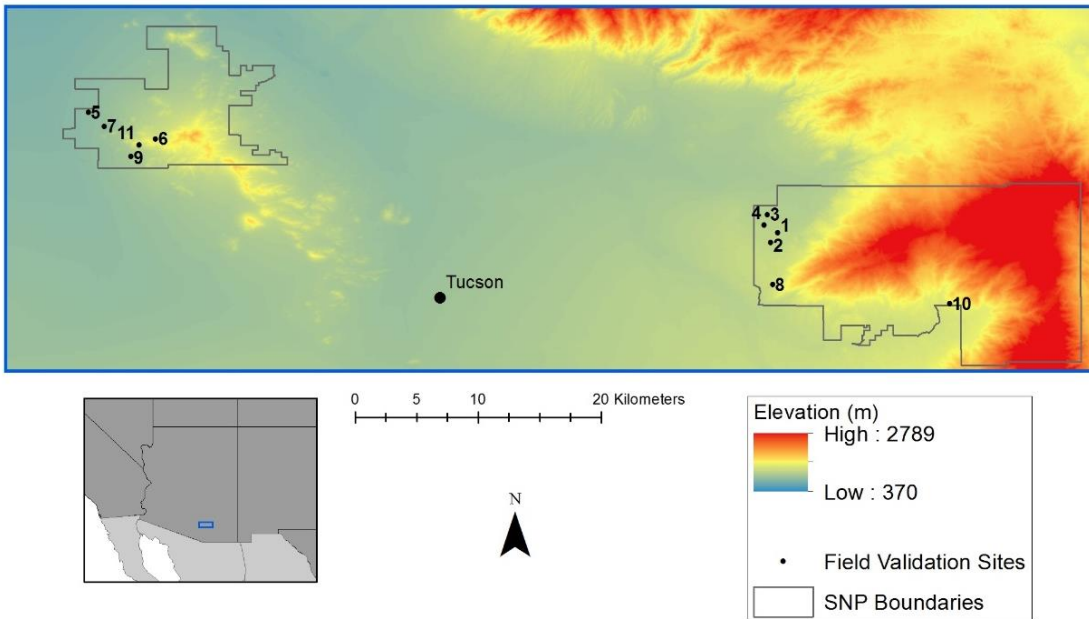


Figure 2. Digital elevation model, SNP districts, and 11 2010 field survey locations. We conducted fieldwork at sites 6 and 8 to investigate saguaros that were missing from the aerial imagery. The Rincon Mountain District is shown to the east of Tucson. The Tucson Mountain District is shown to the northwest of Tucson.

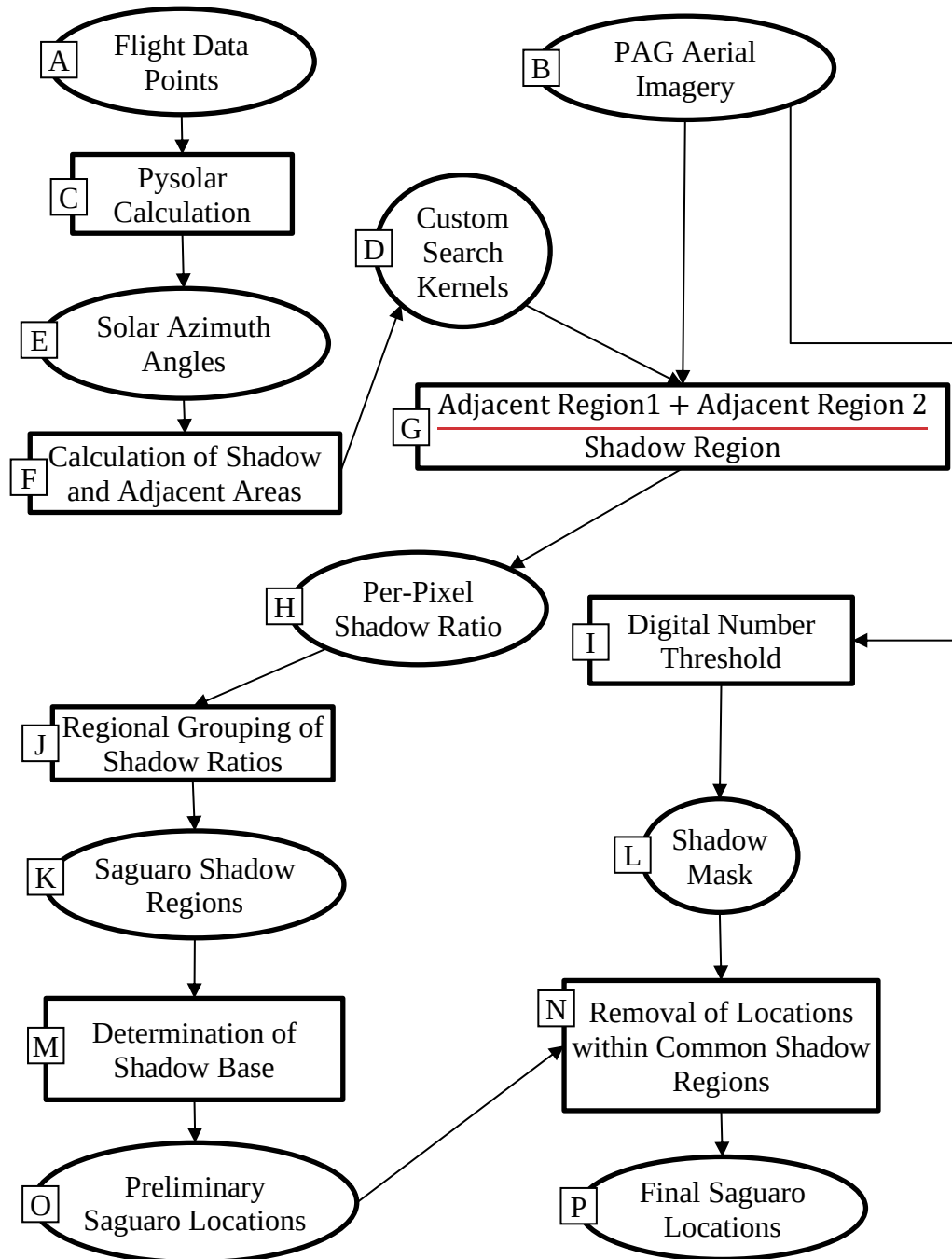


Figure 3. Overview of saguaro detection methodology and workflow. Ovals represent datasets, rectangles represent processes. PAG aerial imagery and flight data points are the primary the inputs. Final saguaro locations are the output.

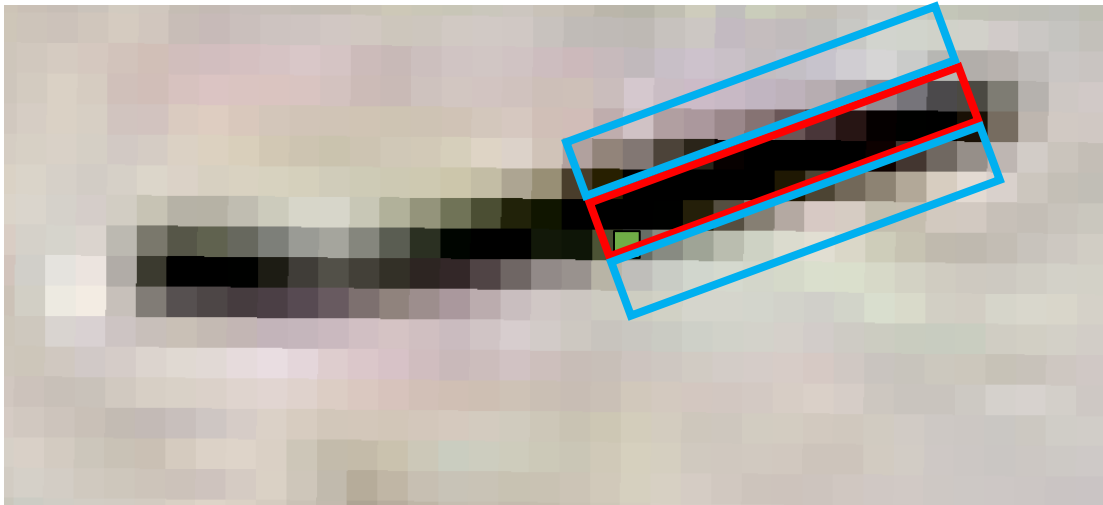


Figure 4. Example of custom kernels being used to calculate saguaro shadow ratios. A target pixel (green square), a shadow search kernel (red rectangle) and two non-shadow search kernels (blue rectangles) are shown overlaid on a subset of natural color digital aerial imagery with a spatial resolution 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 non-shadow 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.

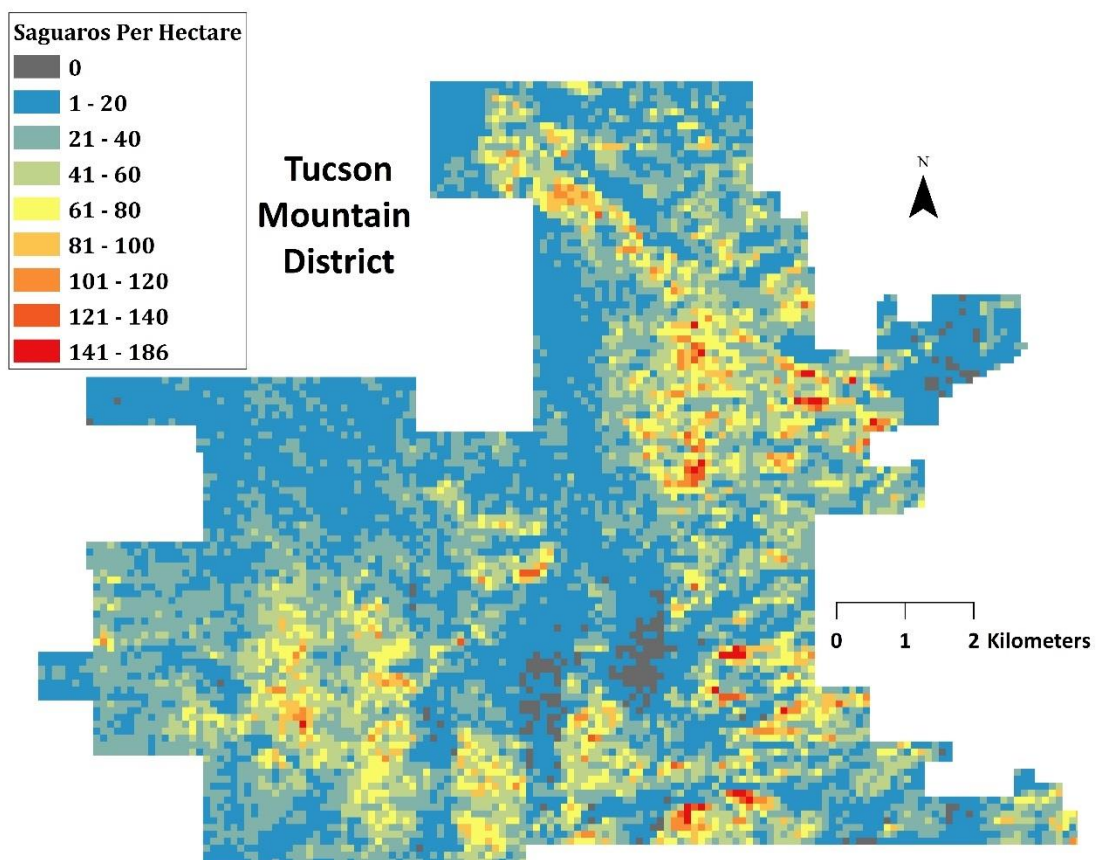


Figure 5. Shadow method results of saguaro density per hectare in Tucson Mountain District of Saguaro National Park in 2011.

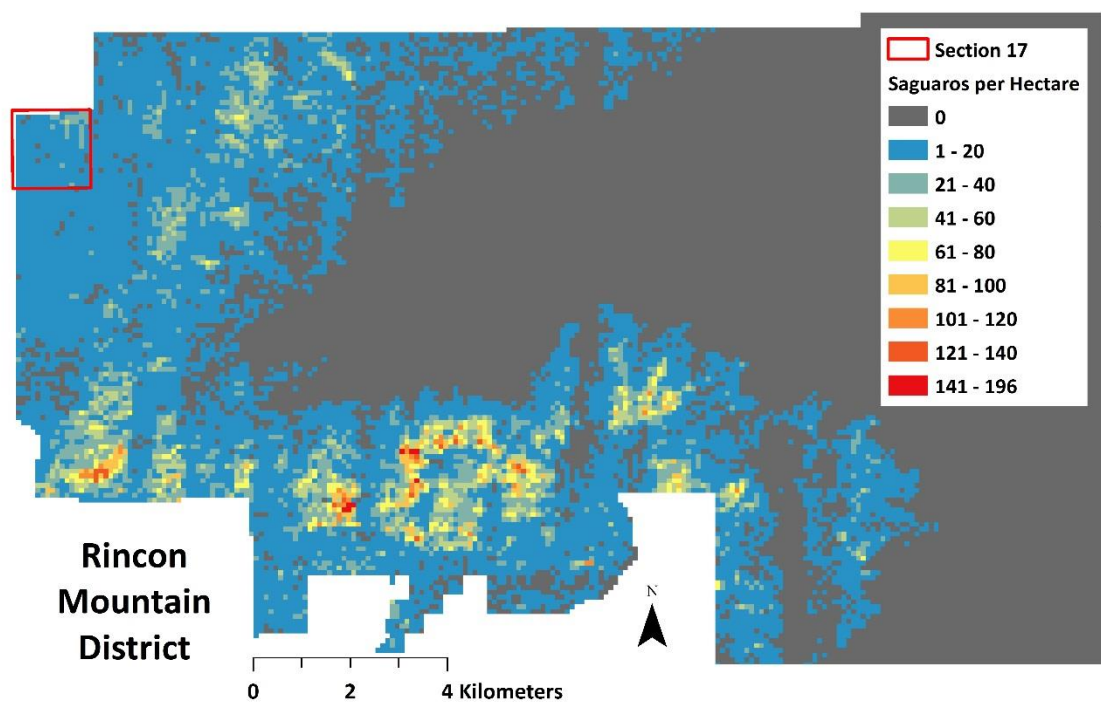


Figure 6. Shadow method results of saguaro density per hectare in Rincon Mountain District of Saguaro National Park in 2011.

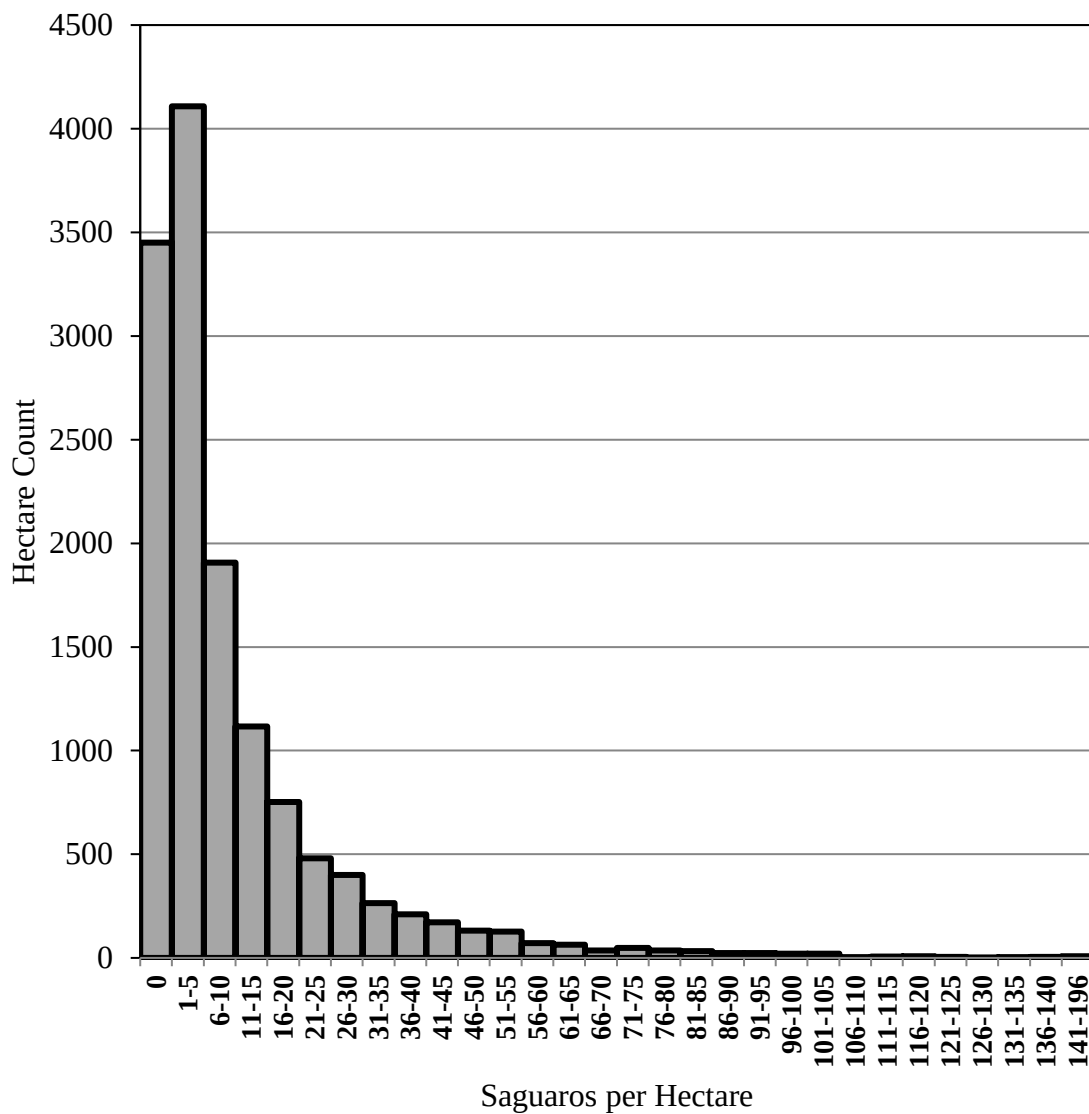


Figure 7. Rincon Mountain District histogram showing the area distribution of saguaro densities (number of saguaros per hectare). Lower bounds of each bin are inclusive, upper bounds are exclusive.

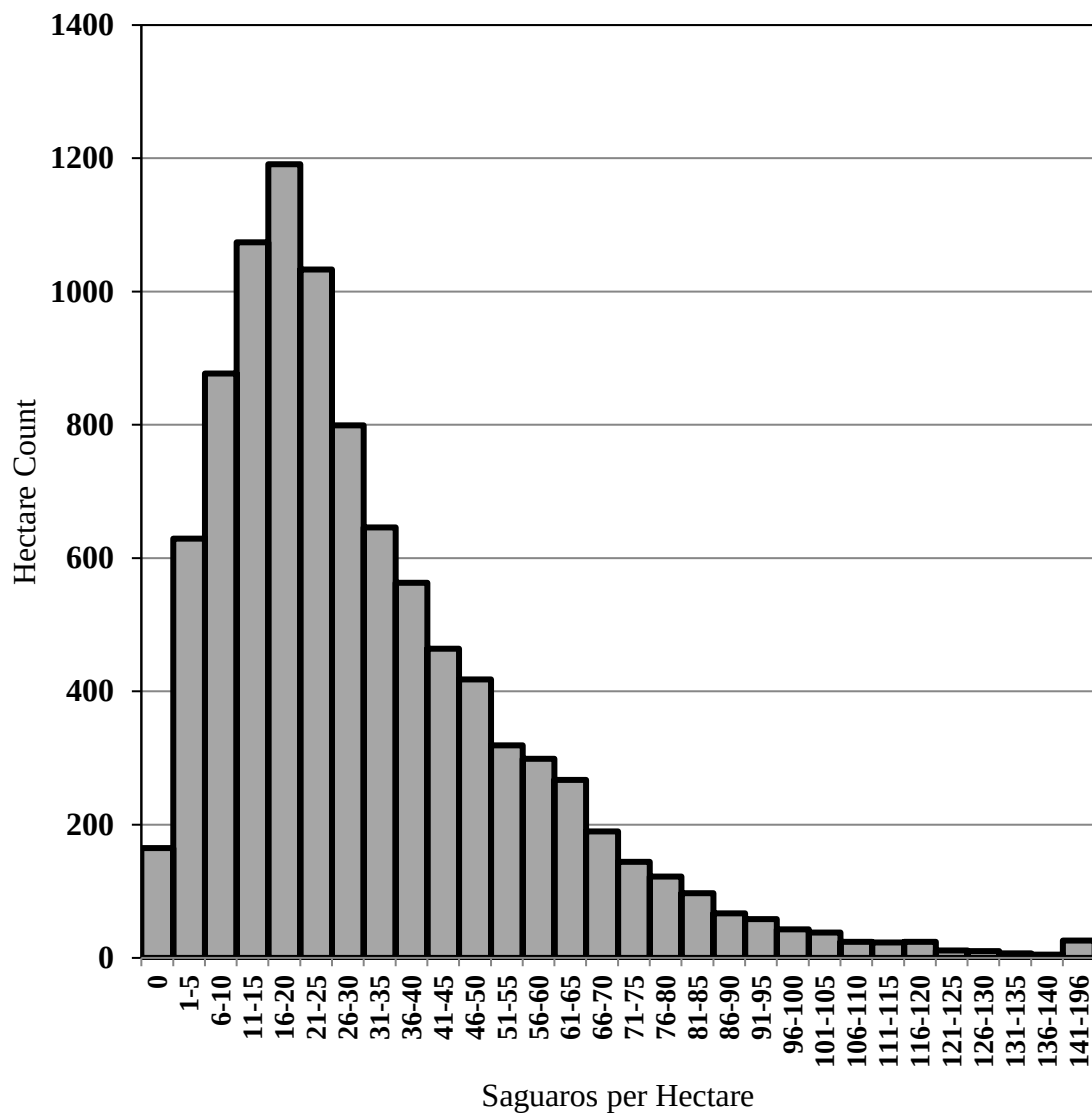


Figure 8. Tucson Mountain District histogram showing the area distribution of saguaro densities (number of saguaros per hectare). Lower bounds of each bin are inclusive, upper bounds are exclusive.

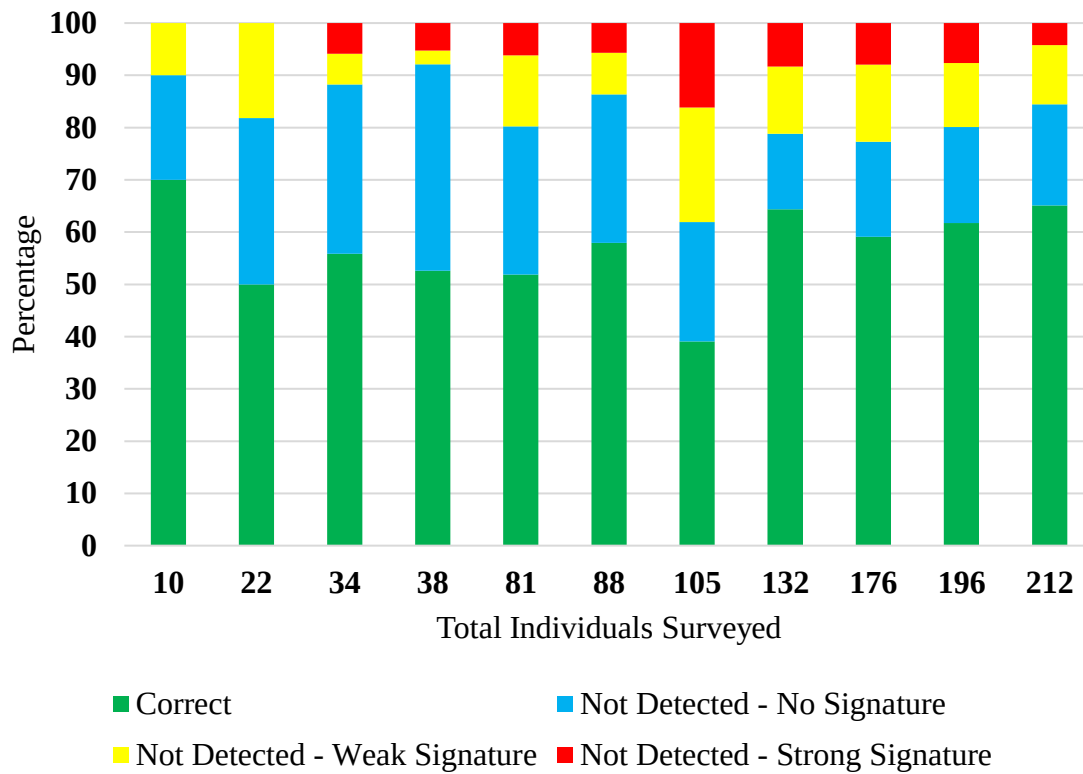


Figure 9. Omission errors derived from the accuracy assessment. Saguaro location data in 11 plots collected by SNP staff in 2010 were compared against the results of the shadow detection methodology applied to 2011 imagery. Omission occurred where a saguaro was located in the field survey plots but was not detected by the shadow method. The overall omission rate was 42.9%

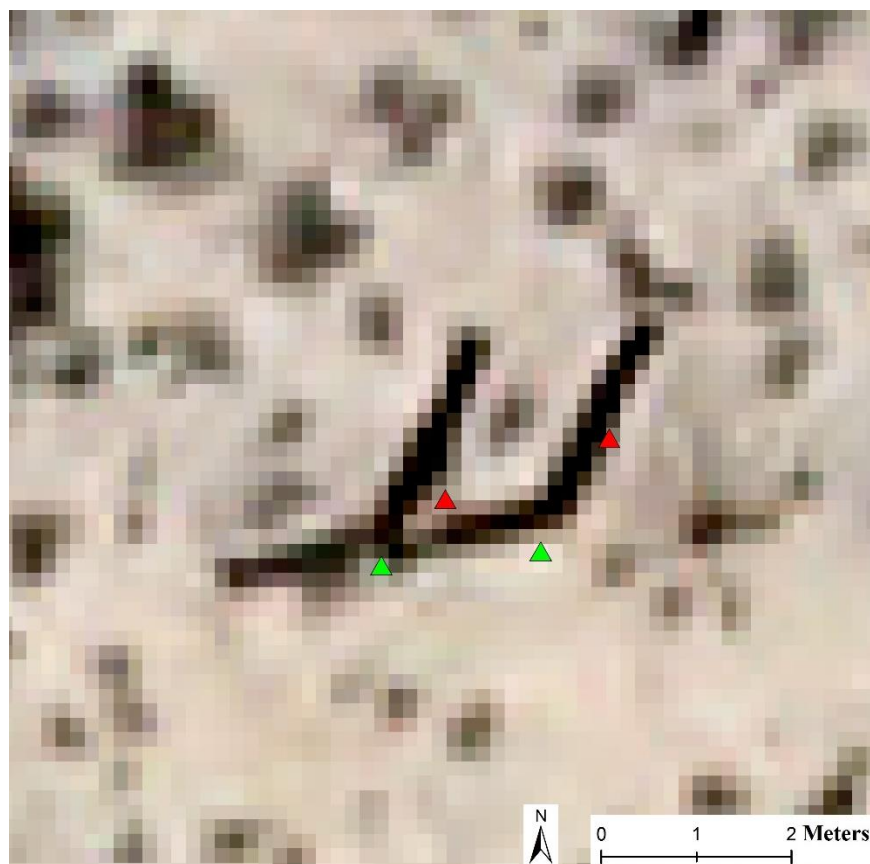


Figure 10A. Multi-spectral imagery showing an example of two correctly identified saguaros. The green triangles mark saguaro locations detected by the shadow method and the red triangles are locations marked in the 2010 field survey conducted by SNP staff.

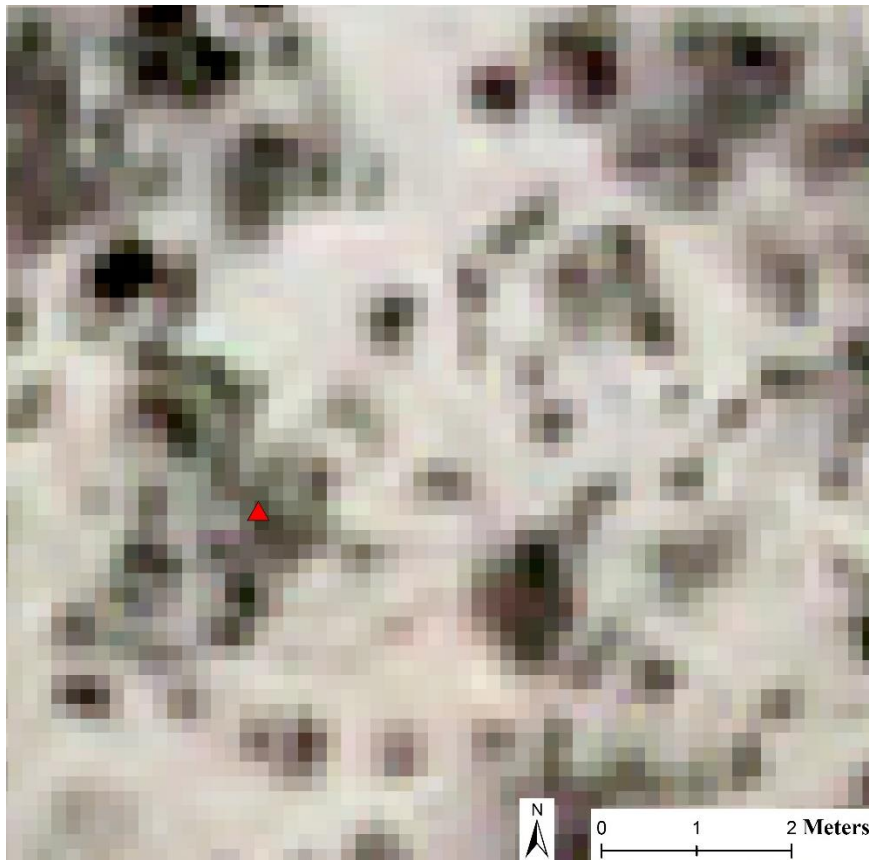


Figure 10B. Multi-spectral imagery showing an example of an omitted saguaro with no shadow signature, likely caused by vegetation. The red triangle is a saguaro location marked in the 2010 field survey conducted by SNP staff. The shadow method did not detect a saguaro shadow in this location.

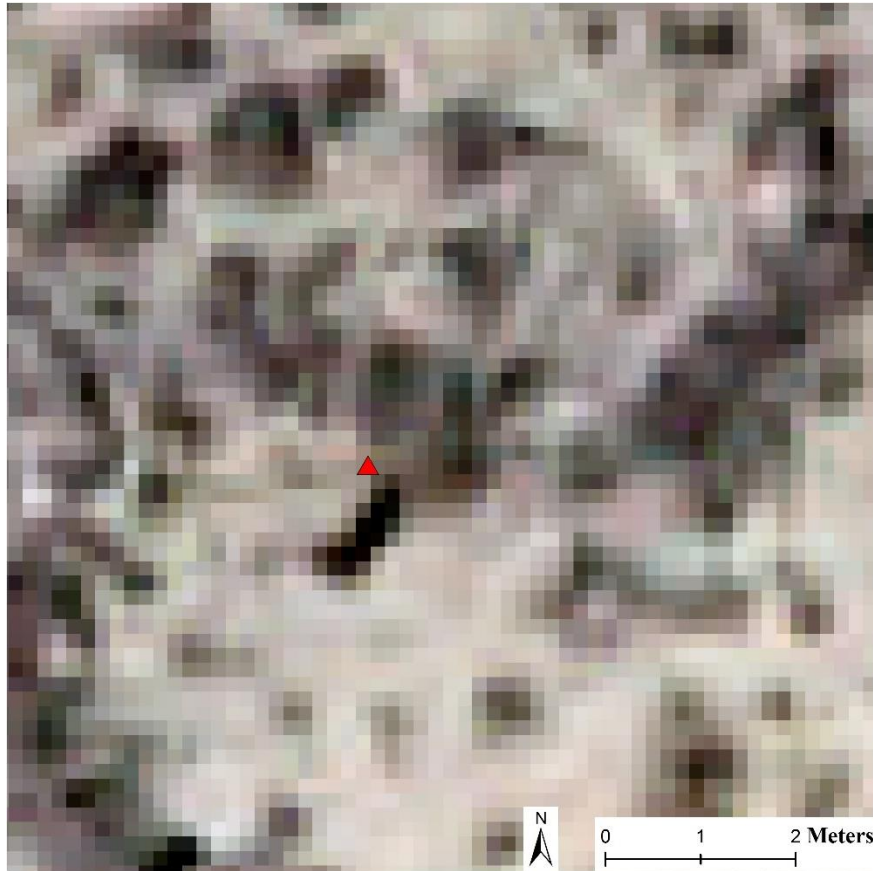


Figure 10C. Multi-spectral imagery showing an example of an omitted saguaro with weak shadow signature. The red triangle is a saguaro location marked in the 2010 field survey conducted by SNP staff. The shadow-method did not detect a saguaro shadow in this location. The shadow signature at the center of the image is short and the contrast between shadow and non-shadow regions is partially obscured. This type of signature would be difficult for a human analyst to detect.

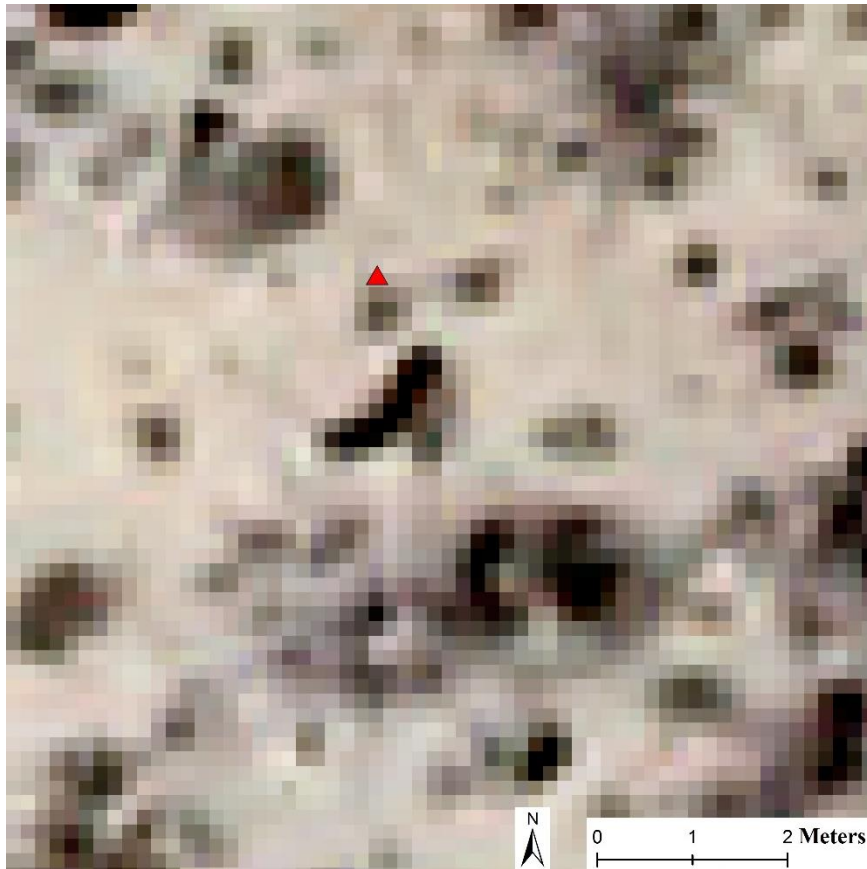


Figure 10D. Multi-spectral imagery showing an example of an omitted saguaro with strong shadow signature. The red triangle is a saguaro location marked in the 2010 field survey conducted by SNP staff. The shadow region directly south of the triangle is likely the saguaro in question. Vegetation may have reduced the contrast between shadow and non-shadow regions, therefore precluding detection by the shadow method. This type of signature would likely be detected by a human analyst.

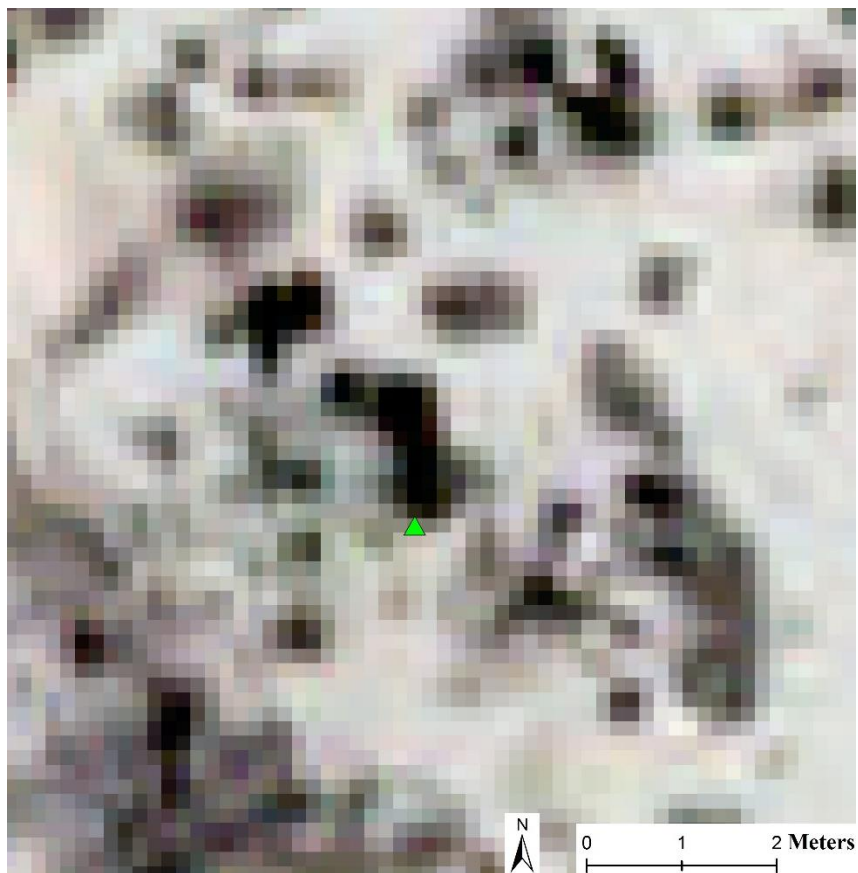


Figure 10E. Multi-spectral imagery showing an example of commission error caused by vegetation. The green triangle shows a saguaro location incorrectly marked by this shadow detection method. The non-saguaro shadow at this location was caused provided sufficient contrast to be detected by the shadow method.

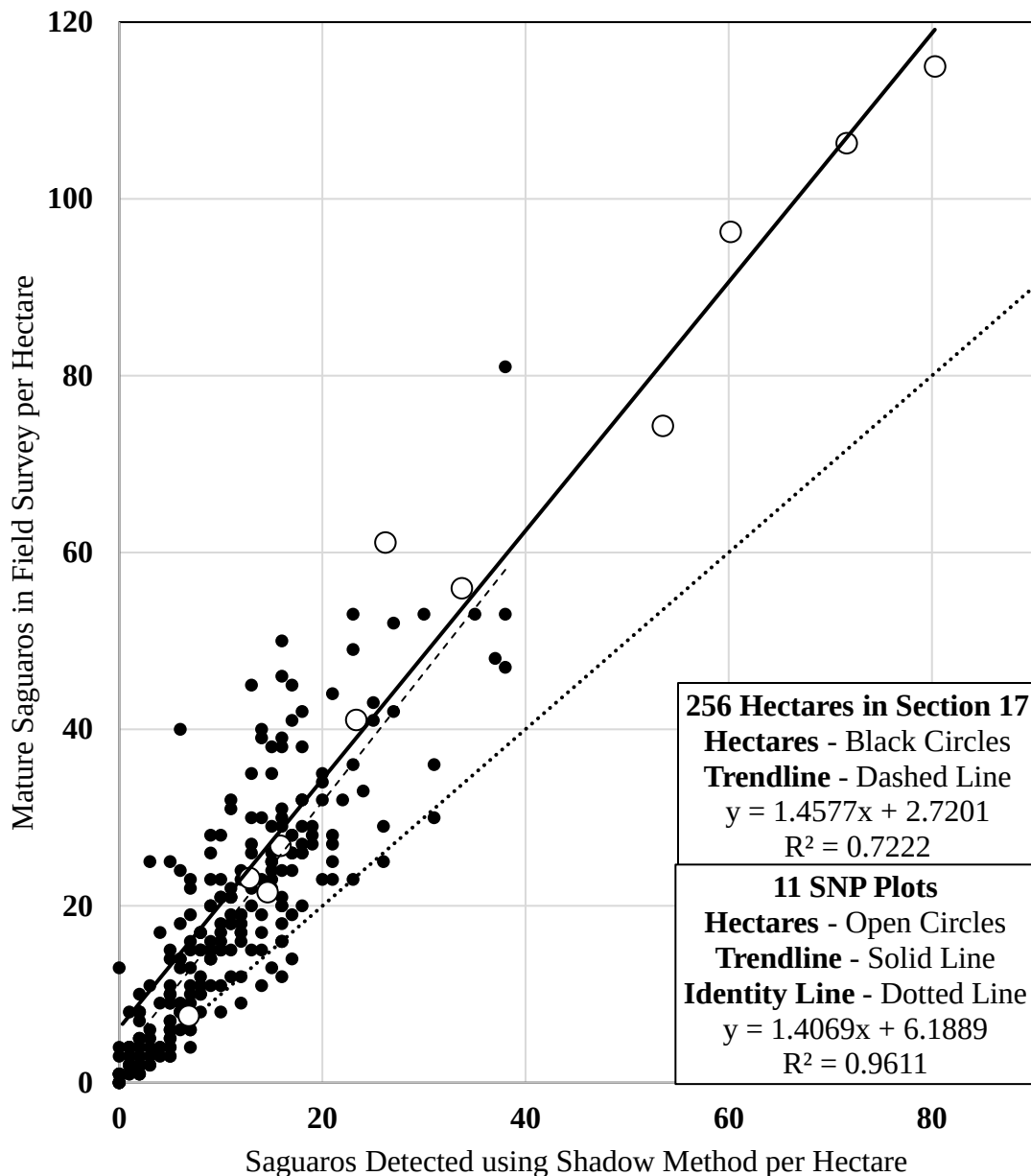


Figure 11. Scatterplot of saguaros detected by the shadow method compared with field surveys of mature saguaros in Section 17 (solid circles) and in 11 spatially distributed SNP plots (open circles). Trend lines are shown as solid and dashed lines, respectively. Each hectare is displayed as a point with 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 (greater than 1.5 meters in height) saguaros identified by *in situ* field surveys. An identity line (1:1 line) is shown as a dotted line.

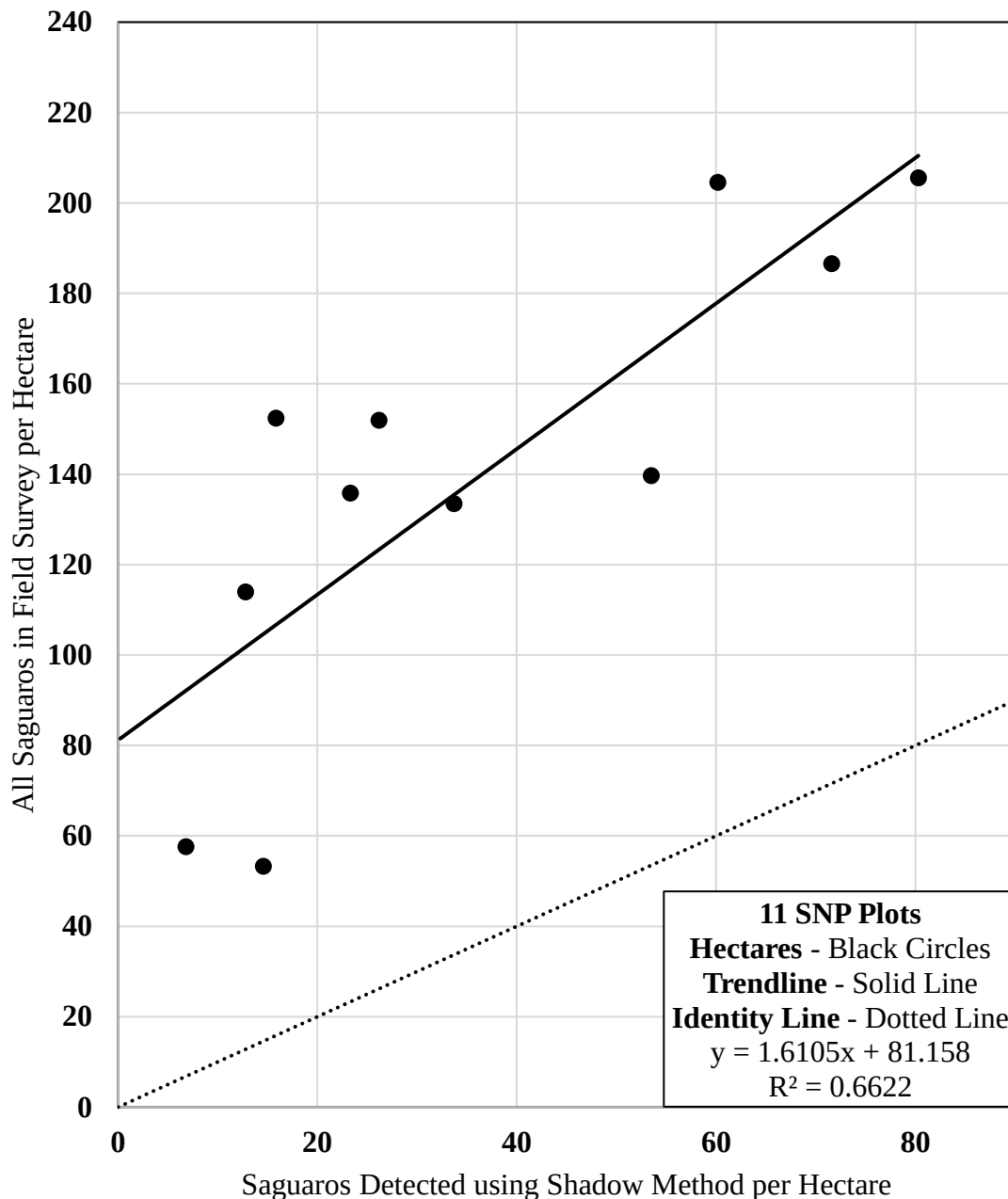


Figure 12. Scatterplot of saguaros detected by the shadow method compared with field surveys of total saguaros in 11 spatially distributed SNP plots. A trendline is shown as solid line. Each hectare is displayed as a point with an x value representing the number of saguaros identified from 2011 imagery by the shadow method and a y value representing the number of total (mature and immature) saguaros identified by *in situ* field surveys. An identity line (1:1 line) is shown as a dotted line.

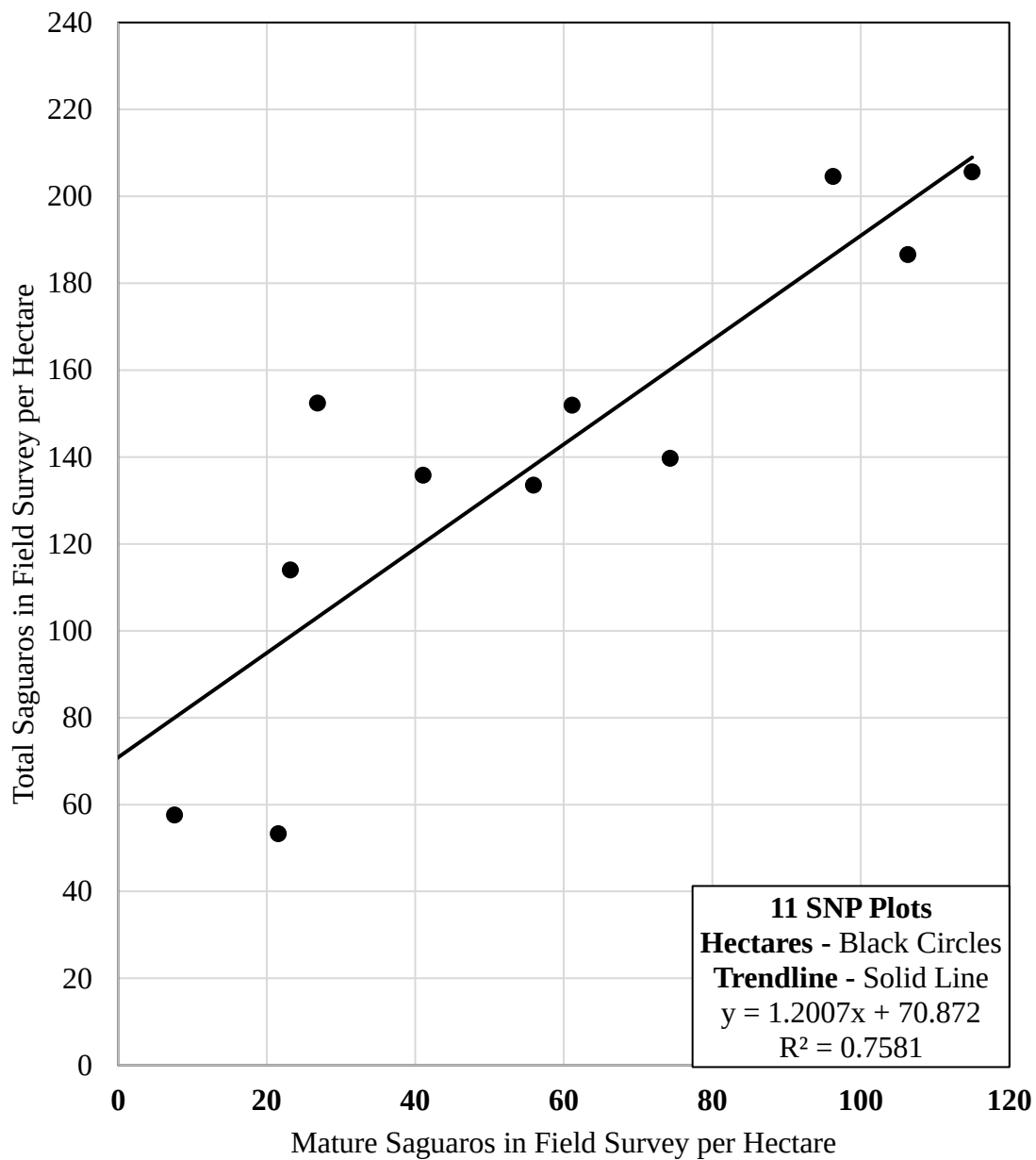


Figure 13. Scatterplot of mature saguaros compared with total saguaros in field surveys of 11 spatially distributed SNP plots. Each hectare is displayed as a point with an x value representing the number of mature (greater than 1.5 meters in height) saguaros located by *in situ* field surveys and a y value representing the number of total (mature and immature) in those surveys.

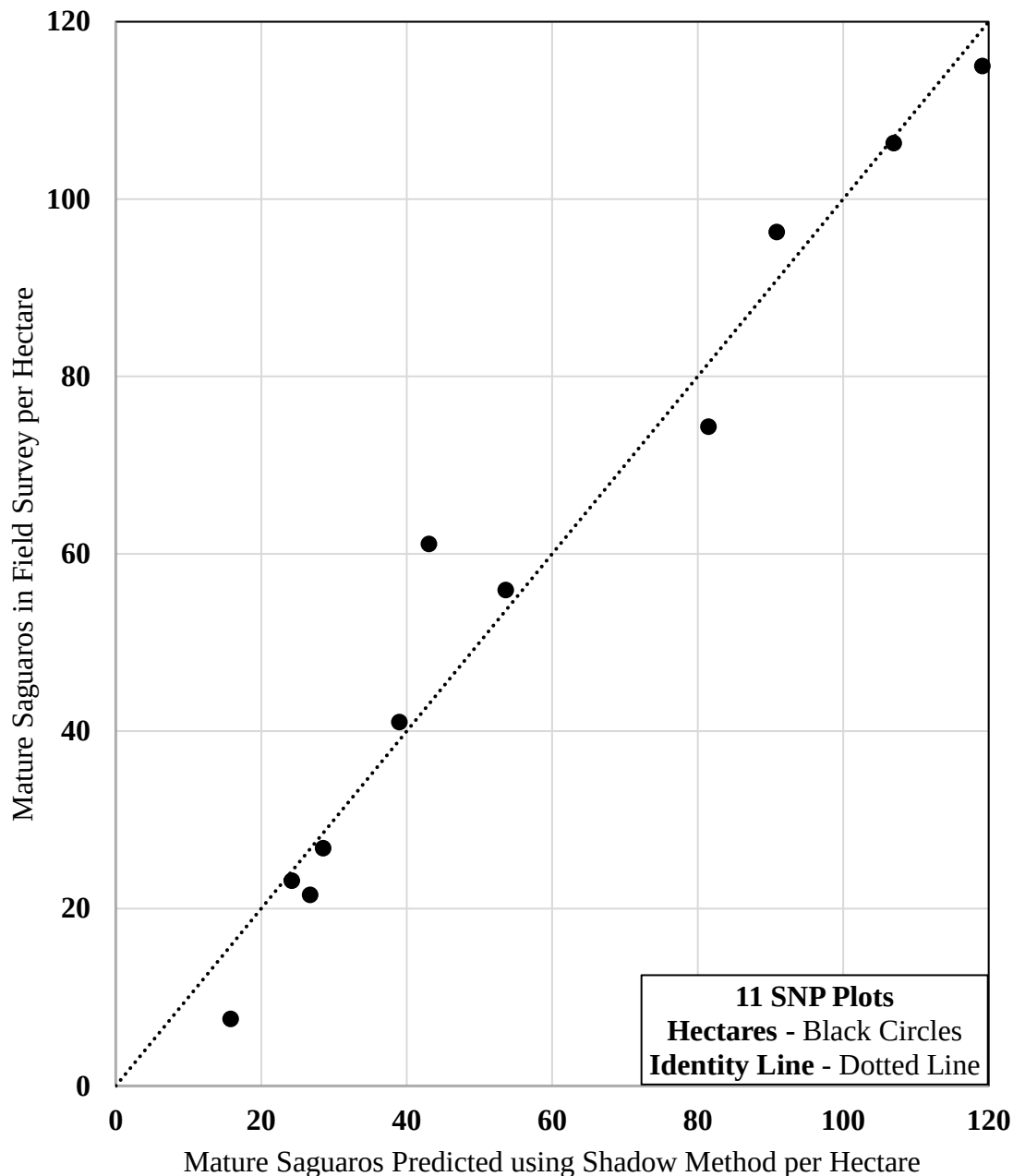


Figure 14. Scatterplot of mature saguaros predicted after linear regression of the shadow method results compared with field surveys of mature saguaros in 11 spatially distributed SNP plots. Each hectare is displayed as a point with an x value representing the number of mature saguaros identified from 2011 imagery by the shadow method adjusted for omission and commission by linear regression and a y value representing the number of mature (greater than 1.5 meters in height) saguaros identified by *in situ* field surveys.

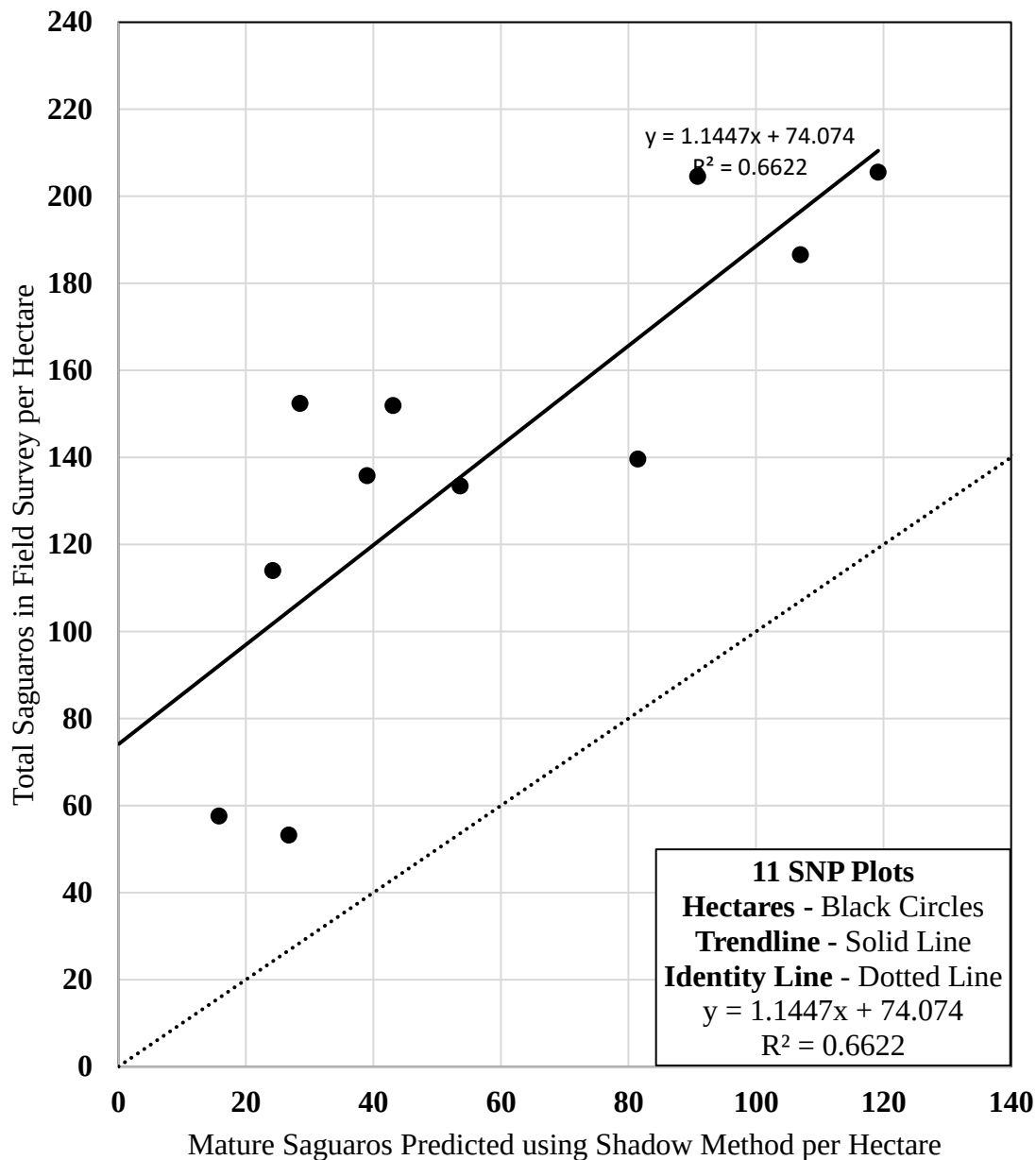


Figure 15. Scatterplot of mature saguaros predicted after linear regression of the shadow method results compared with field surveys of total saguaros in 11 spatially distributed SNP plots. Each hectare is displayed as a point with an x value representing the number of mature saguaros identified from 2011 imagery by the shadow method adjusted for omission and commission by linear regression and a y value representing the number of total (mature and immature) saguaros identified by *in situ* field surveys.

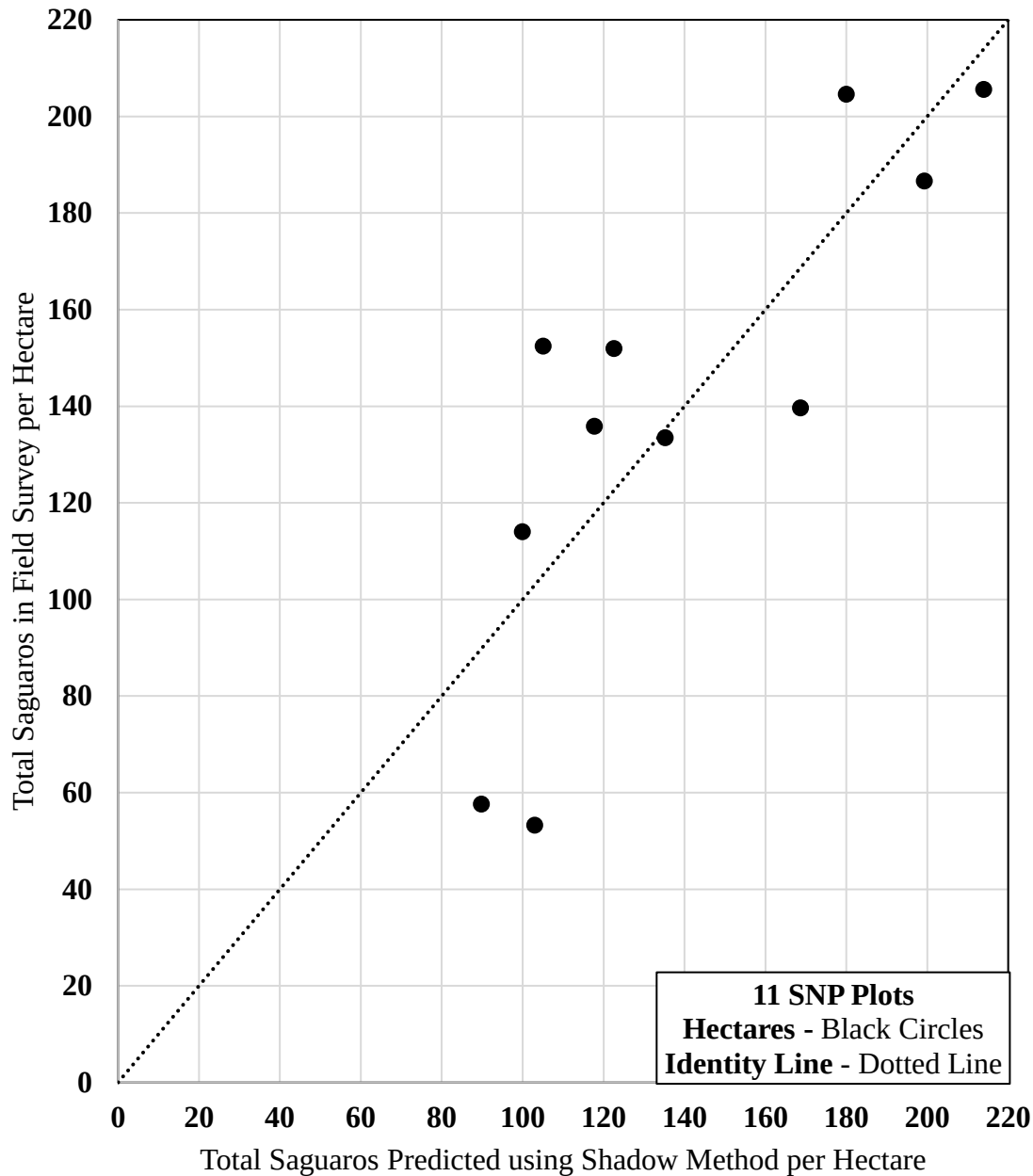


Figure 16. Scatterplot of saguaros detected by the shadow method corrected for commission and omission and corrected for total population by linear regression compared with field surveys of total saguaros in 11 spatially distributed SNP plots. Each hectare is displayed as a point with an x value representing the adjusted total number of saguaros identified from 2011 imagery by the shadow method and a y value representing the number of total (mature and immature) saguaros identified by *in situ* field surveys.