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A History of Saguaro Cactus Monitoring in Saguaro National Park, 1939–2007

Natural Resource Report NPS/SODN/NRR—2009/093

ON THE COVERS

Front: Saguaro cacti, Tucson Mountain District, Saguaro National Park. NPS/E. Ahnmark.

Inside Back: Saguaro cacti, Saguaro National Park. NPS photo.

A History of Saguaro Cactus Monitoring in Saguaro National Park, 1939–2007

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Authors
Eric B. Ahnmark
Don E. Swann
Saguaro National Park
3693 South Old Spanish Trail
Tucson, Arizona 85730-5601

Editing and Design
Alice Wondrak Biel
Sonoran Desert Network
7660 E. Broadway Blvd., Suite 303
Tucson, Arizona 85710

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Acronyms

ha	hectares
NPS	National Park Service
RMD	Rincon Mountain District
SCV	Saguaro Cactus Virus
TMD	Tucson Mountain District
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

Acknowledgements

This report highlights only long-term saguaro plot monitoring surveys completed within Saguaro National Monument (since 1994, Saguaro National Park) as recognized by the National Park Service (NPS) and contained within its archives. Many independent and short-term studies have been done on the saguaro cactus and other Sonoran Desert vegetation in and near the present-day borders of Saguaro National Park since the dawn of the twentieth century. This report by no means covers every one of those surveys. In addition to the researchers and scientists mentioned herein, individuals such as W. V. Turnage, A. L. Hinckley, W. A. Niering, W. T. McDonough, E. E. Snyder, C. Steelink, W. H. Earle, L. Benson, D. C. Bertelsen, and others have completed many short-term and periodic surveys on saguaros. Current work on saguaros owes much of its foundation to these and other individuals for their work and dedication. These lesser-known—but no less significant—studies ranged from the carbon dioxide exchange of saguaros, to determinants of growth, to the characteristics of saguaro tissue fluids. For more information on these surveys, see the literature-cited pages of any of the three installments of Steenbergh and Lowe's "Ecology of the Saguaro" series, or browse sources in the NPS NRBIB-SAGU master file.

Over the past decade, Saguaro National Park has made a great effort to re-locate original plots and data, map plots, digitize the data, and preserve the original work—and to use this work in developing long-term monitoring at the park. The goal is to make these data available for future researchers and managers, so that Saguaro National Park can learn from the work of the past in order to better understand its resources and make informed decisions in the future. Much of the data for this "research atlas" project, preserved with great care by generations of researchers, is now in digital format on the Saguaro National Park network drive.

This report was supported by the Western National Parks Association and the National Park Service. The park is very grateful for the many researchers who have done work at the park over the years and whose work in cited in this report. We are particularly grateful for the ongoing work and support of researchers Ray Turner, Tom Orum, Nancy Ferguson, Carianne Funicelli, and Dale Turner, as well as the summary work of Joseph McAuliffe. We also thank Ray Turner, Tom Orum, Larry Norris, Jeff Balmat, Meg Weesner, Matt Daniels, and Natasha Kline for reviewing this manuscript, and Andy Hubbard of the NPS Sonoran Desert Inventory & Monitoring Network for help in bringing it to publication.

Introduction

Saguaro National Monument was established in 1933, with the aim of preserving the majestic saguaro cactus (*Carnegiea gigantea*) and other plants unique to the Sonoran Desert.* At that time, research on the saguaro had been underway for nearly 30 years, and some evidence already existed that the saguaro population in the Tucson, Arizona, area was declining. Many factors may have been responsible for the decline, including cattle grazing, which led to trampling of both young saguaros and the brush and trees that provided the cover necessary for them to survive. As Tucson and its mining and agricultural-based economy grew, so too did the need for land and wood for homes. Loss of saguaro habitat and the deforestation of local timber increased through the early and middle decades of the twentieth century. Even after the monument's establishment, both grazing and illegal collection of firewood continued within its borders for many years. In addition, major freezes during the winters of 1937, 1940, and 1941 damaged or killed many of the older and larger saguaros (Steenbergh and Lowe 1983).

In response to the obvious saguaro decline observed throughout the monument in the late 1930s, efforts to establish saguaro monitoring plots commenced in 1941, with the assistance of the U.S. Department of Agriculture (USDA) Agricultural Research Service. From these early "cactus-disease investigations" blossomed a multi-faceted network of saguaro monitoring projects, several of which continue today. Collectively, data from these studies have revealed a great deal about the decline and recovery of the saguaro population at the park, and have provided insight into some of the factors that affect the park's signature cactus.

The main purpose of this report is to summarize, clarify, and relate the comprehensive and often convoluted web of saguaro research and monitoring undertaken at Saguaro National Park since its founding (see timeline, Figure 5). This report is by no means a complete summary of every study carried out within the park, nor does it highlight much of the work performed on saguaros outside park boundaries. The focus here is on long-term studies for which data are currently available, with the objective of summarizing the methods, goals, location, history, personnel, and results of each monitoring effort. This document can also be used as a literature review to facilitate future monitoring projects. Figures 1 and 2 illustrate the locations of all plots from each major long-term monitoring project. Each separate project and corresponding plot spread is then discussed in more detail, in chronological order.

SHANTZ COLLECTION, UNIVERSITY OF ARIZONA HERBARIUM

Homer L. Shantz, President of the University of Arizona, in the Cactus Forest, 1930.

The State of Saguaros, 1910–1939

Surveys of Forrest Shreve

In 1909, Forrest Shreve's surveys on the rate of establishment of the saguaro became the first recorded and published monitoring project concerning this unique giant cactus. Shreve's work focused chiefly on the saguaro population on Tumamoc Hill, a site just east of the Tucson Mountains and the present-day Tucson Mountain District (TMD) of Saguaro National Park. His surveys focused on growth rates and recruitment. According to his report, Shreve took "an exact census . . . of some 240 giant cacti, which formed the entire population of a portion of the northern slope of Tumamoc Hill, including easterly and westerly slopes. All the unbranched individuals less than 5 m. in height were measured."[1] Shreve's findings represent

*The monument became Saguaro National Park in 1994.

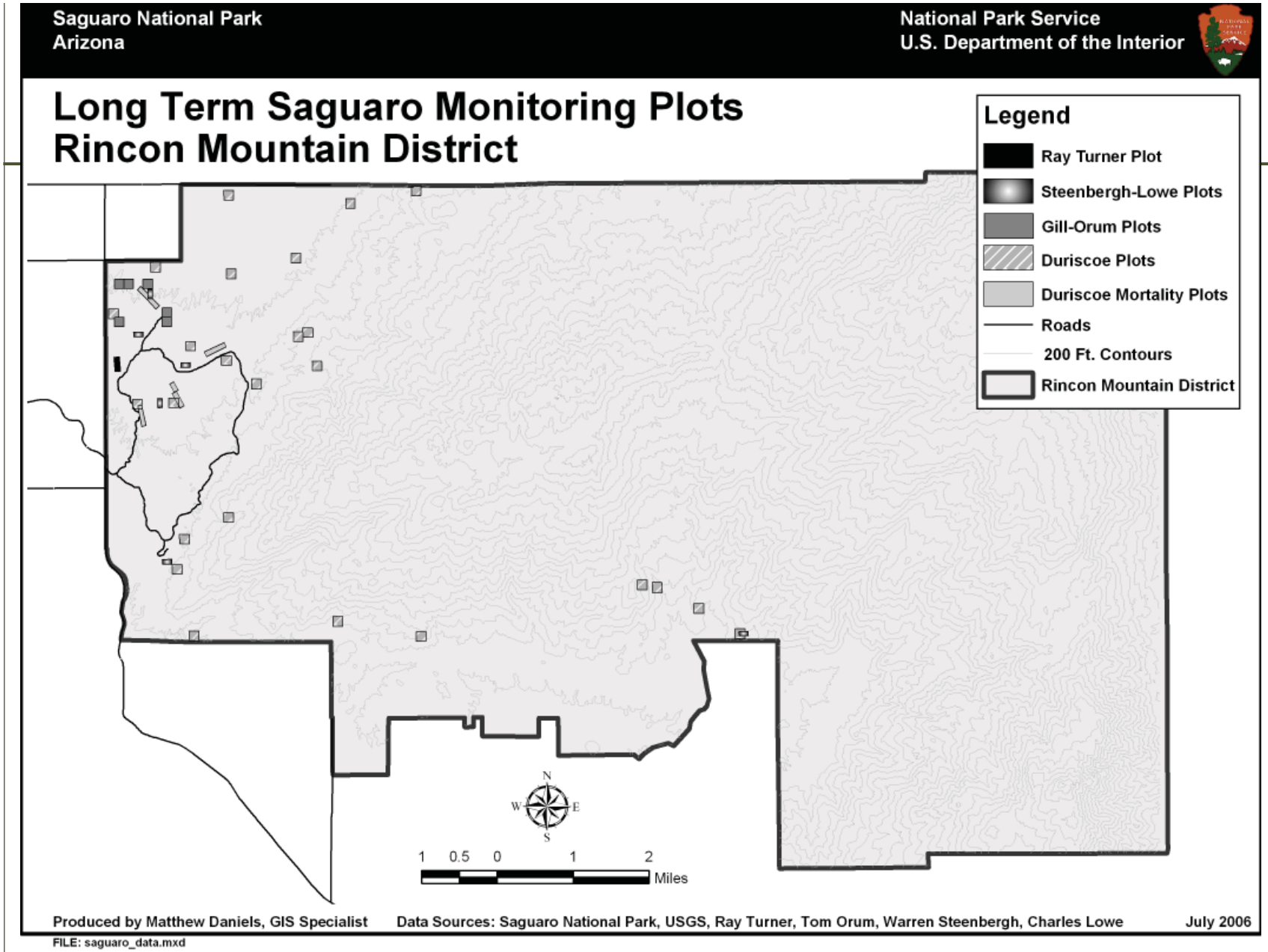


Figure 1. Combined plot locations in Saguaro National Park, Rincon Mountain District. Section 17, where saguaro experiments took place in the 1940s, is located immediately north of Loop Drive, directly under the "notch" in the park's northwest corner.

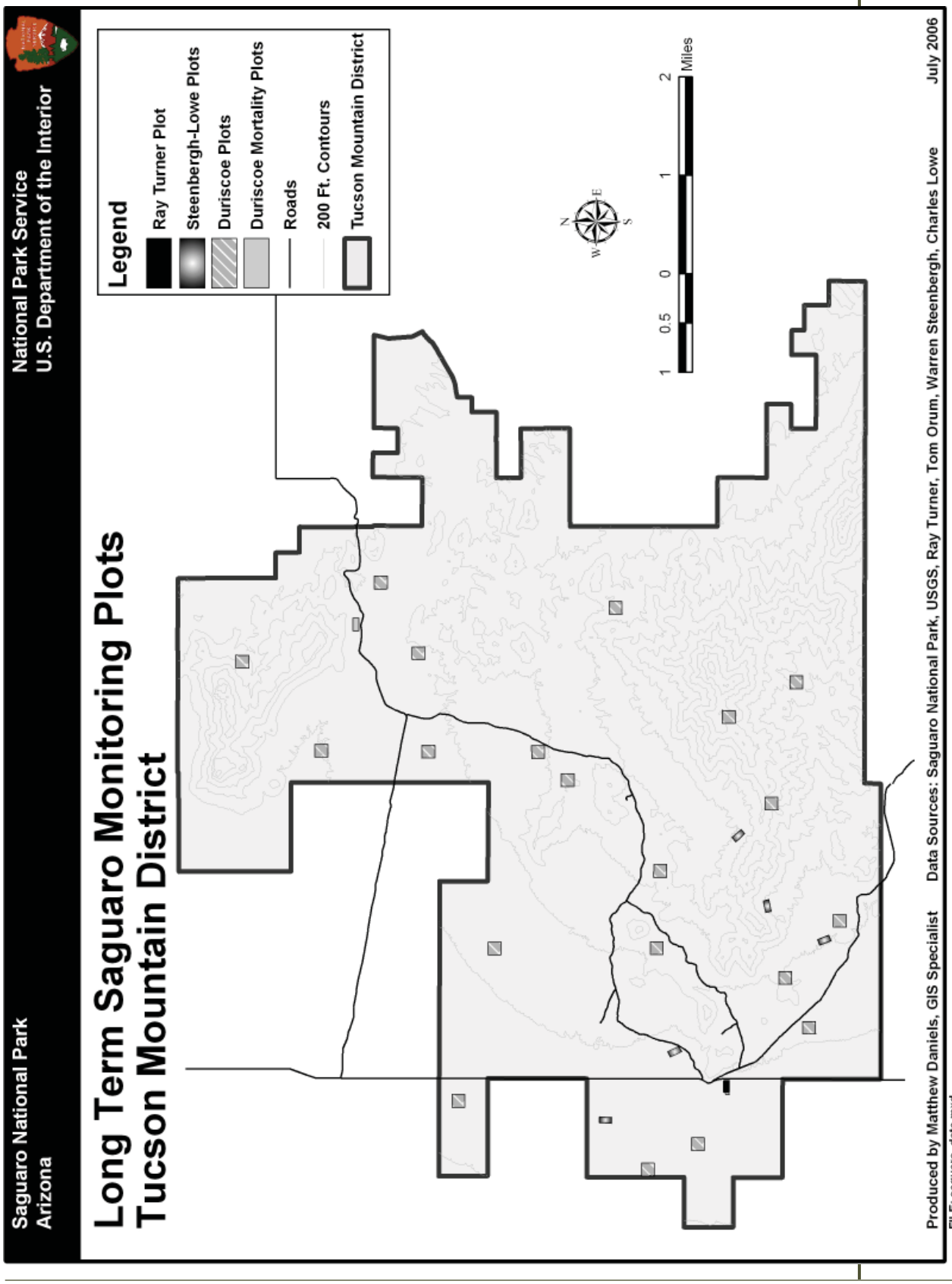
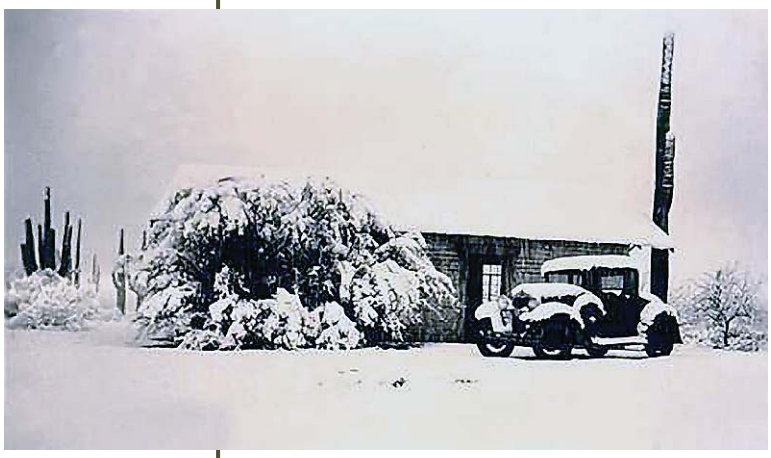


Figure 2. Combined plot locations in Saguaro National Park, Tucson Mountain District.

some of the first preliminary data on density, growth, and duration of saguaros.

The individuals under 5 m in height—which is to say, those less than 60 years old—formed 36% of the total population, which would indicate an average life expectancy of 175 years for the giant cactus in this location and habitat. There was a noticeable lack of young and middle-aged plants, and an abundance of fallen skeletons, on the steep, rocky, flanking slopes of the hill. The number of younger plants was greater on the gentle slopes facing east and west, which indicates that erosion may have been one of the most important factors in limiting the length of life.[2]

In addition to collecting establishment and density data, Shreve did a great deal of work on the effects of freezing temperatures and frost on saguaros. In his 1911 report, "The Influence of Low Temperatures on the Distribution of the Giant Cactus," Shreve concluded that successive hours of freezing temperatures were the saguaro's most significant limiting factor. This consensus was reached through a series of laboratory tests in which saguaros were exposed to varying hours of frost conditions, and also through field observations of the saguaro stand near Tumamoc Hill.



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Saguaros in snow, 1937.

Shreve's work, although performed at a time of limited technology and botanical knowledge, represented a momentous leap forward in the study of Sonoran Desert plant life. His research, in the early decades of the twentieth century, provided a strong foundation of data on saguaro growth, establishment, and limiting factors upon which future scientists could base their research. Shreve was also first to note a decline in saguaro recruitment rates: "The striking fall in the establishment rate of the Giant Cactus . . . compels the conclusion that it is not maintaining itself. A fuller knowledge of its germination and the behavior of its seedlings, together with a more complete knowledge of the periodicity of certain climatic elements within its range, will be sure to throw light on the fall in its rate of establishment."[3] The recommendations within this statement would come to embody the evolution and maturation of saguaro monitoring throughout the following century. For more information on Forrest Shreve's initial rate-of-establishment and limiting-factor surveys, see Shreve (1910) and Shreve (1911).

Surveys of C. S. and J. C. Wilder

Following the establishment of Saguaro National Monument, a survey similar to that of Forrest Shreve was performed in 1939, by Carleton S. Wilder and Judith C. Wilder. Their study focused primarily on saguaro population density and recruitment. Their survey area comprised three separate locations, each representative of the habitats upon which saguaros are found (lower desert floor, upper desert pocket, and foothill). The quadrant locations were not randomly selected. Instead, "The quadrants were selective; however, in the choice of the general area for counting and in consciously tending, once the line was started, to make counts where small saguaros were seen."[4]

Saguaros in the "lower desert floor" section were found to be taller and denser, on average, than anywhere else in the park. Observations were also recorded about the relative occurrence of saguaro cacti and palo-verde, a plant that would later be identified as one of the saguaro's preeminent nurse plants. The location for this portion of the survey was listed as near the public campground, approximately two miles from the north entrance gate in the present-day Rincon Mountain District (exact location unknown).

The "upper desert pocket" habitat was "formed by the abrupt Observatory Hill [near the northern junction of the park's current Loop Road with the Cactus Forest Trail], rising about a mile north and west of the curving base of the Tanque Verde mountains."[5] Here, the saguaros were not observed as being clumped around palo-verde, as they had been in the lower des-

ert terrain. Instead, mature saguaros stood alone, and small saguaros (those less than 6 ft in height) were plentiful and located predominately beneath or near palo-verde and other desert scrub.

The "foothill" observations were made at the north end of the Skyline Loop Road, where steep slopes transcend to the Tanque Verde ridge. The greatest abundance of small saguaros (those less than 6 ft in height)—many of which were growing beneath the granite boulders that composed the rocky slope—were found here.

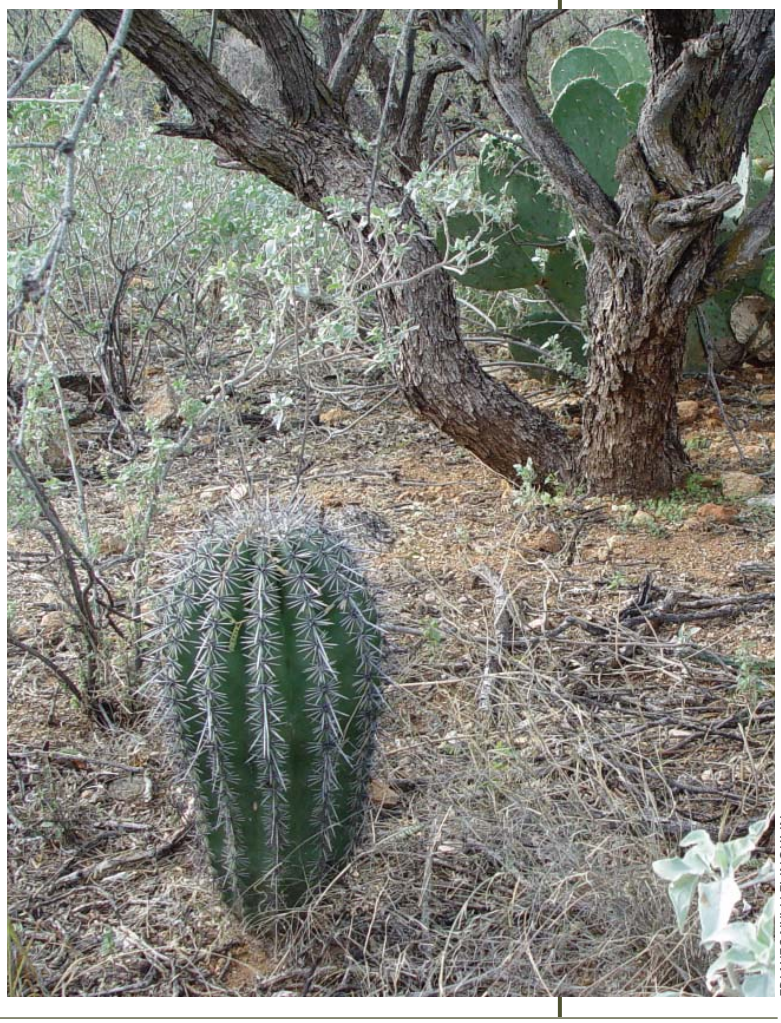
The conclusions of the Wilder study generally complemented those of Shreve's Tumamoc Hill survey 30 years prior: the saguaros in the densest location (lower desert floor) were not replacing themselves as efficiently as the populations at the other two test locations. According to the Wilders, "the number of young plants indicates the possibility of a denser stand of mature trees in the future than exists on these areas at the present time."[6] Such results were alarming to park staff, in that the park's esteemed Cactus Forest was not displaying sufficient levels of recruitment. These findings from the Shreve and Wilder surveys played a major role in fueling a panic about saguaro extinction at the monument that lasted nearly 50 years. For more information on the Wilder census survey, see Wilder and Wilder (1939).

Identifying the Agent of Decline, 1940–1960

The U.S. Department of Agriculture: Section 17 (1940)

Long-term monitoring of saguaros at Saguaro National Monument began in 1940, at the request of the USDA Bureau of Plant Industry, whose officials initiated cactus-disease investigations after noting an increase in the spread of bacterial necrosis (epidermal rot) on mature saguaros. For this experimental survey, a portion of the northwest corner (S17, R16E, T14S) of Saguaro National Monument (Rincon Mountain District; RMD) was chosen (see Figure 1). This so-called "Section 17" was divided into northern and southern halves, each of which covered approximately 320 acres, for a total test area of 640 acres. The objective of the USDA project was to test the effectiveness of sanitation measures at deterring the spread of necrosis. The plan called for all infected saguaros and saguaro limbs from the southern "half" to be removed, burned, and buried, while the "data from the north half [were to] serve as a check or means of judging the effectiveness of the sanitation work."[7] The progress of each half was then to be checked annually for the following five years. Figure 3 shows the 640-acre USDA test area.

Each half was divided into 10-acre quadrants, and each quadrant was subsequently labeled. According to a 1942 report on the project, "The staking [for the southern half] was begun in September 1941 and completed in January 1942; 12,968 living saguaros were thus identified."[8] Data on saguaro height, mechanical injuries, and disease condition were gathered at the time of staking. Similar information was gathered for the northern half from February through March 1942. Infected plants that



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Young saguaro under cover of a mesquite "nurse tree" (*Prosopis velutina*) in the Rincon Mountain District, Saguaro National Park.

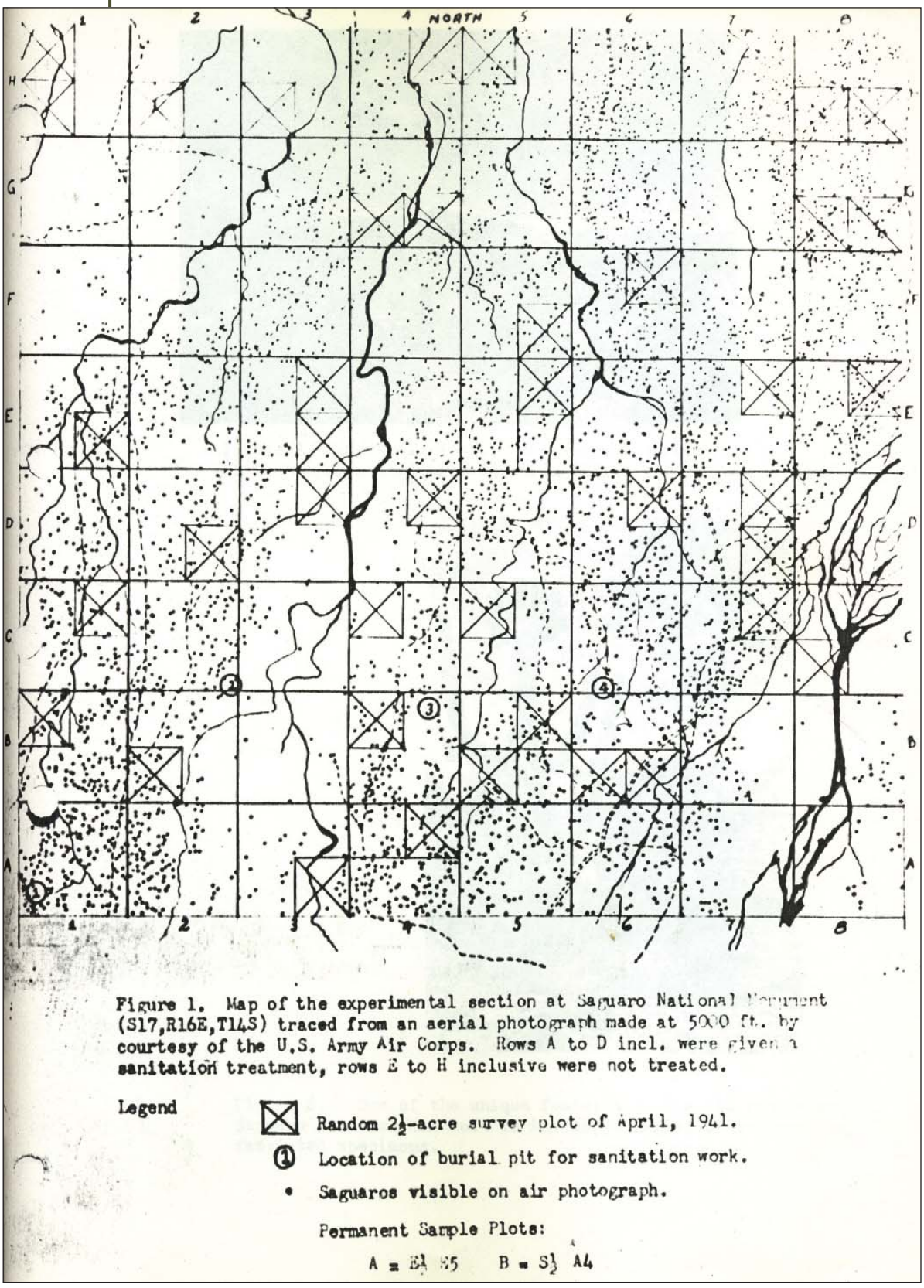

Figure 3. Map of the USDA experimental test area, "Section 17" (Gill 1942). Individual saguaros, mapped using a detailed aerial photo, are represented by a single black dot. A copy of this map is available at the Western Archeological and Conservation Center and a digital copy is on the Saguaro National Park server.

warranted removal were felled and removed from February 16 to 20, 1942, with more than 313 diseased plants removed.[9] Sanitation work was executed simultaneously: "Cacti marked for removal were felled, bucked, loaded on trucks, and dumped into one of four pits which had been previously excavated on the area. The cacti in the pits were fumigated with a concoction of paradichlorobenzene and kerosene and then covered with at least a foot of earth."[10] Over the course of the two years for which data were recorded, a striking decrease was found in the origination and spread of bacterial lesions. However, over a longer period, there was no difference in mortality between the treated and untreated sections (Gill 1951). For more information on the USDA cactus-disease investigations, including methods, results, photographs of the investigations and necrosis progression, as well as recorded data from similar investigations at Organ Pipe Cactus National Monument and the Tucson Mountain Park, see Gill (1942).

Gill and Lightle: The 5-acre plots (1941)

The first permanent plots intended for repeated and long-term monitoring were established in the fall of 1941, in tandem with the USDA cactus-disease investigations. Researchers Lake S. Gill and Paul C. Lightle established the plots, while simultaneously spearheading the Section 17 project. The goals of this survey were (1) to learn to recognize the developing stages of bacterial necrosis, (2) to observe the progress and behavior of bacterial lesions and the cactus's healing abilities, and (3) to determine the cause(s) of the disease.[11] As with the USDA study, Gill and Lightle performed similar research at Organ Pipe Cactus National Monument. The long-term objective was "to establish permanent observation plots in the Saguaro and Organ Pipe Cactus National Monuments on which detailed case histories shall be kept. Thorough reexamination will be made at stated intervals."[12]

Monitoring began in April 1941, and consisted of six 5-acre (2-ha) plots in and near the Cactus Forest of today's Rincon Mountain District. These plots were numbered 41A–F and marked by a wooden stake in the southwest corner (see Figure 6a).[13] Data were recorded on saguaro density, height, estimated age, and health (mechanical injuries, disease condition). The six plots were revisited three times after their initial establishment in 1941, and although they were originally intended for regular study, their existence was nearly forgotten; 34 years passed before they were resurveyed. In 1975, W. F. Steenbergh and C. H. Lowe discovered data from Gill and Lightle and revisited all but one plot, collecting critical and unprecedented data on growth, mortality, and recruitment that spanned nearly 40 years. Gill and Lightle's 5-acre plots were resurveyed again in 2002, by C. S. Funicelli and D. S. Turner. More information on these resurveys is discussed later in this report.

Little information is known about the precise data recorded at Gill and Lightle's 5-acre plots in 1941–42, other than the rudimentary height, density, and recruitment figures listed in Steenbergh and Lowe's resurvey in 1975. Data from these plots were recorded in Steenbergh (1980 and 1986).

Gill and Lightle, Alcorn, and Orum: The 10-acre plots (1941)

In addition to their six 5-acre plots, Gill and Lightle also established six 10-acre plots. These were also located in the Cactus Forest area (present-day RMD), in and around the vicinity of Section 17. Figure 4 shows the exact locations of these plots. It is not known for certain why Gill and Lightle established these plots simultaneously with their six 5-acre plots, nor why they showed diminishing interest in their 640-acre site and all but abandoned their 5-acre plots, yet continued annual resurveys of their 10-acre plots. However, statements in Gill (1951) on saguaro mortality lend to the notion that the 10-acre plots (comprising 60 acres compared to 640 acres) were established to enable a more intimate study of each saguaro and its immediate environment.

Impressively, with the exception of 1955, these same six plots have been surveyed annually since 1942, "and their condition, including mortality, noted. In addition, a search is made for young saguaros, their location is noted on a map, and their height measured. The heights of all saguaros under six feet tall are measured each year. Heights of taller saguaros are estimated in 6 foot height classes and, periodically, are estimated using a clinometer."[14] Gill and Lightle, in association with S. M. Alcorn, recorded data on the six 10-acre plots from 1942 through the

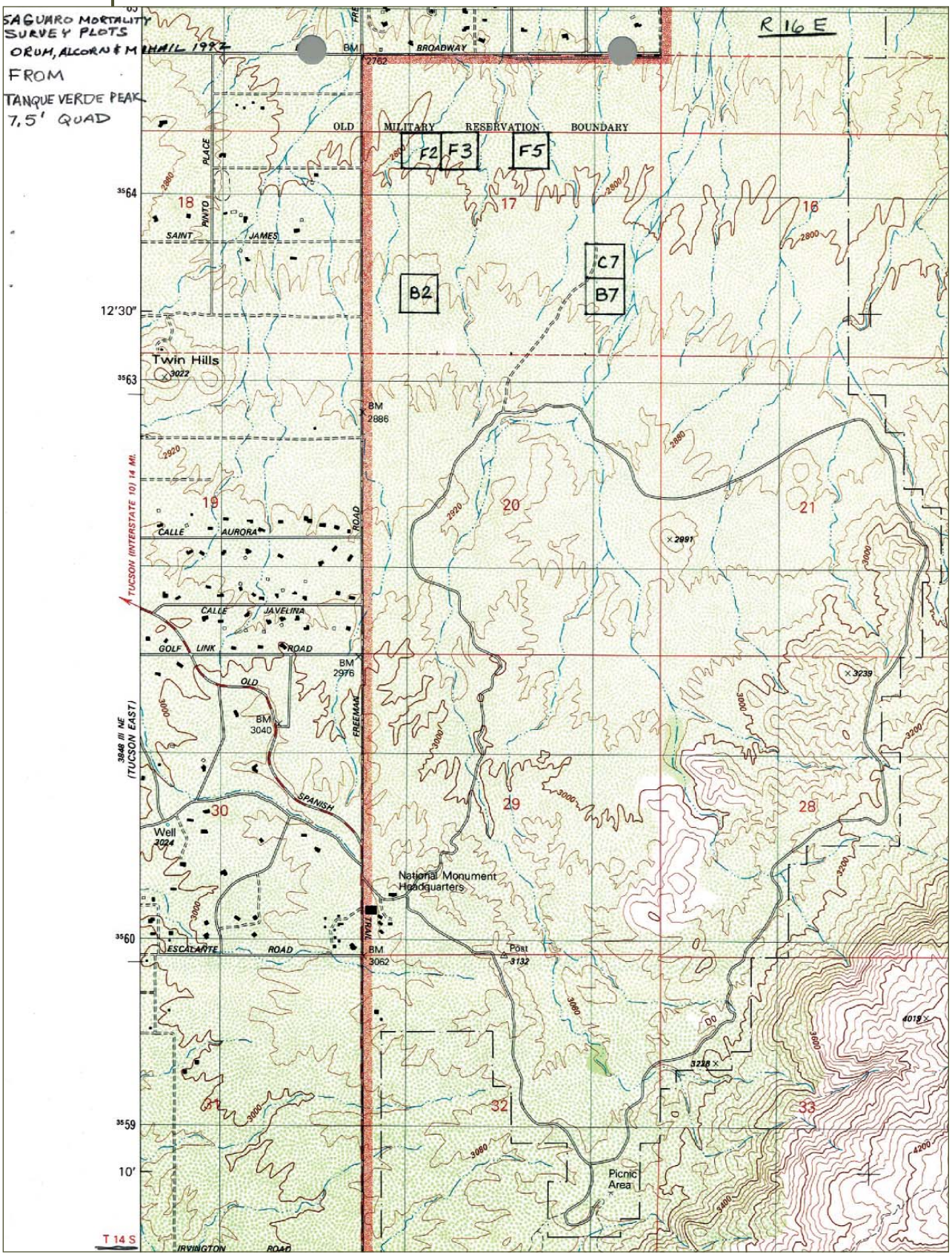

Figure 4. Gill and Lightle's original six 10-acre plots within Section 17 in the present-day Rincon Mountain District (Orum and Alcorn 1991). For reference, note the park headquarters and Cactus Forest Loop Drive.

mid-1950s, when Alcorn took over.

S. M. Alcorn became one of the saguaro's most prolific and dedicated researchers, publishing a great number of reports that focused predominantly on the pollination and germination of the giant cactus. One of Alcorn's more elaborate long-term studies ran from January 1942 through January 1961, and was summarized in the report, "Attrition of a Saguaro Forest" (Alcorn and May 1962). This mortality survey reported on different causes of saguaro death, with an emphasis on bacterial necrosis. Alcorn's conclusions were grim. Not only had bacterial necrosis accounted for 29% of saguaro mortality over the course of the 20-year survey, but the combined effects of grazing (not eliminated on monument property until 1958) and wind also resulted in soil erosion that seriously impeded the growth of seedlings. These findings led Alcorn to conclude that "the sparsity of juvenile plants indicates that this saguaro forest is failing to maintain an adequate rate of natural repopulation. . . . the continual attrition of this forest by BN [bacterial necrosis] and wind is . . . eroding the base for repopulation."[15] For more information on this long-term mortality survey, see Alcorn and May (1962).

In 1979, Alcorn passed his monitoring of the six 10-acre plots on to researcher Tom Orum, Alcorn's former research technician who, with his wife, Nancy Ferguson, have continued to monitor these plots for almost three decades. With the change in leadership came a change in direction; whereas in earlier years, the surveys had tended to focus on mortality and the progression of bacterial necrosis, both the latter years of Alcorn's surveys and Tom Orum's resurveys reverted toward study of saguaro density and recruitment. Orum avers that it is inevitably the saguaros, not the researchers, who deserve the credit for the change in focus (T. Orum, pers. comm.); saguaro recruitment increased so prolifically during the late 1970s and early 1980s that Nancy Ferguson even suggested changing the name of the project from "mortality surveys" to "annual saguaro census."

To date, this set of surveys represents the longest ongoing saguaro-monitoring effort in the park. Although the methods have remained relatively consistent over the past 60 years, survey focus and results have changed significantly. While earlier findings, from the Gill-and-Lightle era, exhibited a steady and alarming decrease in the saguaro population—"between 1942 and 1972, almost no new saguaros were found"—a recent influx of growth and recruitment over the past 20 years has largely diffused concern for the saguaro's immediate future.[16] Orum has noted that after reaching an apparent low point in 1982, by 1985, "the observed original population seem[ed] to have deviated slightly in the positive direction from the predicted decline."[17] By 1990, the number of young saguaros in the 10-acre plots outnumbered members of the original population for the first time since recording began in 1942.[18] Much to the satisfaction of all those concerned with the fate of the saguaro, the results published in Orum and Alcorn's 1991 "Report on the Long-term Saguaro Mortality Study" found saguaro recruitment to be on the rise. Orum, Mihail, Alcorn, and Ferguson also published supplemental reports in 1998 and 1999, both of which confirmed his encouraging results from 1991. More information on the ongoing Gill-and-Lightle/Alcorn/Orum surveys can be found in Orum (1991, 1998, 1999).

Continued work in Section 17 (1944–1960)

While focusing on their six 10-acre plots, Gill and Lightle also continued intermittent research and follow-up at the Section 17 site. A February 1944 report on the progress of treated saguaros from the 1941–42 sanitation procedures led to encouraging and intriguing results. From the time the study began in 1941 until the resurvey in 1943, some 587 additional saguaros had died on the entire 640-acre test area. Of these, only 187 (32%) were on the southern (sanitized) section, whereas the remaining 400 (68%) were on the untreated northern section.[19] In addition, by this time, the bacteria were presumed to be transmitted through a certain moth larvae, making the felling and burial of diseased saguaros unnecessary. Additional studies showed that many lesions could be eliminated simply by removing them from the cacti and allowing the plant's natural healing process to take over.

Further data from the 1943 survey led to Gill and Lightle's 1946 resurvey and publication on mortality. They discovered that, overall,


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Juvenile saguaro. By the 1990s, increasing numbers of younger plants began to quell fears of a saguaro "extinction."

mortality seemed to be decreasing since the study's beginning, six years prior. However, due to the slow growth and regeneration of saguaros, it was unclear whether or not this decrease could be attributed, in part, to the USDA sanitation efforts. This uncertainty, combined with the brevity of the survey, led to the absence of any long-term mortality predictions. Gill resurveyed the area again in 1951, for a 10-year reconnaissance. Using data from 1943 and 1946, he found there to be no significant difference between the treated and untreated areas.[20] Gill also concluded that stem rot was positively associated with cactus height (and presumably age). This, combined with the general absence of stem rot on younger specimens (those less than 12 feet in height), led to the consensus that bacterial necrosis was not as threatening a disease as once perceived, and was unlikely to obliterate the saguaro as a species. Gill's 1951 findings effectively brought an end to bacterial sanitation efforts. More information on these two surveys, as well as their results and findings, can be found in Steenbergh (1986), Gill and Lightle (1946), and Gill (1951).

In 1945, Alice M. Boyle conducted a survey that looked deeper into the causes and spread of bacterial necrosis. Her search focused on how the disease was spread through the larvae of a common moth, *Cactobrosis fernaldialis*, whose young carry the bacterium and infect the cactus.

Finally, another one of Alcorn's studies, led by Ray Turner, ran from July 1957 to July 1967. This study took place on the USDA test area, but encompassed more than the aforementioned six 10-acre plots. In this survey, young saguaros "were transplanted into 80 plots within a 4-ha tract on level terrain . . . on July 8–10, 1957."[21] Sixteen treatment combinations were surveyed; some plots were caged to deter rodents, some plots were watered, others shaded. More than 1,800 saguaros were planted, 1,600 of which were less than 5 cm in height. The results from the plots varied significantly. All plants in the unshaded and uncaged plots died or vanished within months of planting. Survival in the caged, although not rodent-proof, plots was more than twice as high as the uncaged plots.

The study changed slightly in 1958 and 1963, when the researchers added the element of rodent-proof cages and included plots at varying altitudes. The cages, buried to a depth of 15 cm, completely inhibited rodent access; interestingly, these sites experienced the highest rate of mortality by insects. Results from the plots at different altitudes were inconclusive, other than that average mortality was highest in the "mountain plot," and lowest in the "lowland plot." For more information on this 10-year mortality and transplant survey, see Turner et al. (1969).

Return to the Census, 1961–present

Turner and Hastings: The 9.2-acre plots (1961–2006)

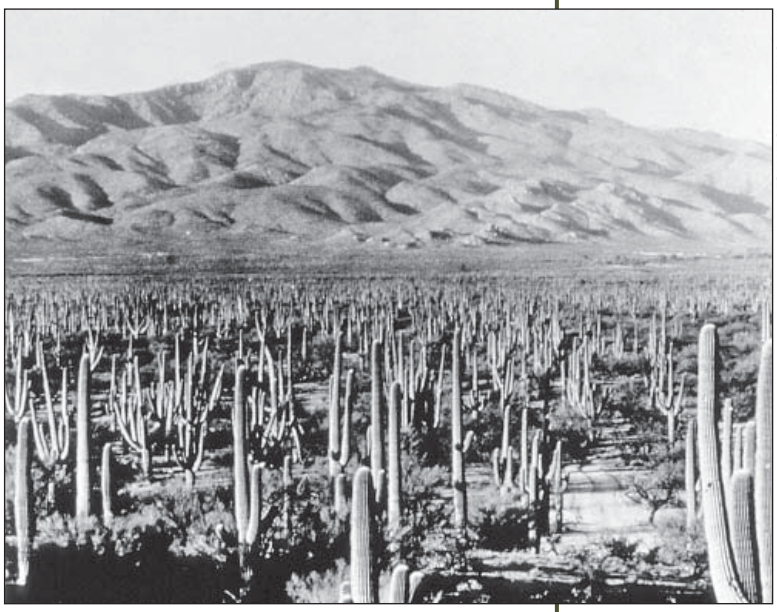
In the 1960s, a large-scale effort for long-term saguaro monitoring was initiated by researchers R. M. Turner and J. R. Hastings, authors of the well-received book on long-term vegetation change, *The Changing Mile*. Turner and Hastings established a set of ten 400 × 1000-ft (9.2-acre) plots throughout southern Arizona and Sonora, Mexico. Of these ten, one was located in each of the two districts of Saguaro National Monument. The plots were reexamined five times up until 1989; they were most recently re-

mapped and resurveyed in 2005–2006.[22]

The plots have been monitored at intervals averaging about 10 years, during which data on mortality, growth, and recruitment have been recorded.[23] One of the important findings of these plot studies has been the marked increase in new recruitment that has occurred during the past 20 years, within the area of the original RMD Cactus Forest. This abundance of young cacti represents a "phenomenal population surge," and has the potential to become a new saguaro forest in the next century.[24]

Turner and Hastings also discovered that although mortality in the RMD plot was significantly higher than in its TMD counterpart, recruitment in the RMD was also significantly higher than in the denser, healthier TMD plot. This suggested that the widespread fear of saguaro attrition and extinction in Saguaro National Monument was unfounded; the RMD Cactus Forest was not, in fact, "dying out." Rather, the old, mature cacti were dying due to natural causes. Turner and Hastings felt that the fear of saguaro extinction existed simply because not enough consideration was given to life cycles—specifically, recruitment. In the latter stages of this survey, "attrition" had given way to an unprecedented surge in recruitment—such that by 1989, 76% of the RMD plot population had been established since the beginning of the study in the early 1960s.[25] Conversely, the "younger" TMD saguaro stand was slowing in recruitment levels, and represented a different level in the saguaro's episodical cycle of growth. It is now generally believed that if present trends continue, the now-majestic saguaro stands in the TMD will resemble the present-day RMD stands in 50–100 years, and the now meager RMD Cactus Forest may return to its 1940s splendor.

Aside from quelling the extinction panic, Turner and Hastings's survey also played a significant role in advancing the effects of prolonged drought as one of the principal limiting factors of saguaro growth. According to their survey, amidst the 20-year "population surge" there was a single year of variance, 1976, which was defined by extremely low levels of recruitment. This year also corresponded with one of the most severe droughts in the Tucson area since the beginning of the twentieth century.[26] As such, this survey not only shed encouraging light on the saguaro's life cycle, but also provided further insight into the giant cactus's limiting factors. For more information on other studies of the saguaro's limiting factors, see McAuliffe (1993). A full report of Turner and Hastings's results from the TMD and RMD plots can be found in Turner (1989). In 2006, Ray Turner and his colleagues completed another round of surveys on these plots, but the results were not published as of this writing.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Top: Cactus Forest, Saguaro National Monument, 1935.

Bottom: Cactus Forest, same view, 1998. If present trends continue, this area may return to its former splendor in 50–100 years, representing a period of episodic growth.

Steenbergh and Lowe: Resurvey of Gill and Lightle's 5-acre plots (1971–1975)

Among the major contributors to modern knowledge of the saguaro were Warren F.

Steenbergh, of the National Park Service, and the eminent ecologist Charles H. Lowe, from the University of Arizona. Steenbergh and Lowe, who did a number of studies in both Saguaro and Organ Pipe Cactus national monuments, published their findings in three books: *Ecology of the Saguaro I*, *II*, and *III*, published in 1976, 1977, and 1983, respectively. In 1971, the two researchers established a single, 2-ha (100 × 200-m) plot, labeled 71G, near Kinney Road in the TMD, in which all living saguaros were tagged, recorded, and surveyed annually through 1975, when four additional 2-ha plots were established.[27] One additional 2-ha (100 × 200-m) plot, labeled 75M, was established in 1975, approximately one mile east of the Madrona Ranger Station, to provide long-term data on saguaros growing on south-facing slopes.[28] Also in 1975, the two researchers stumbled upon information that led to the relocation of Gill and Lightle's 5-acre RMD plots from 1941. Of the original six, only five were re-established and resurveyed: plots 41A–F, with the exception of plot 41E.

Data retrieved from these 11 plots, primarily height and density information, documented a 34-year period of change (see Figure 5). Overall results from this resurvey were consistent with other density conclusions from the time: the saguaro was continuing to decline, although some areas were beginning to show increased recruitment of young saguaros. More information and data from this 1975 resurvey, including copies of original field maps and data on saguaro height and density, can be found in Steenbergh (1986) and Steenbergh and Lowe (1983).

Following the 1975 resurvey, these 11 long-term plots were not studied again for another 27 years. However, Steenbergh and Lowe left behind documentation of their work, and the plots were resurveyed in 2002 by Carianne S. Funicelli and Dale S. Turner. Figures 6a and 6b show the locations of the 11 long-term plots from Steenbergh and Lowe's 1975 establishment and survey. Plots 41A–F represent Gill and Lightle's original six 5-acre plots from 1941 (again, plot 41E was not relocated). More information on Funicelli and Turner's 2002 resurvey will be discussed later in this report.

Duriscoe and Graban: 45 new plots (1988–1989)

The next major step in long-term saguaro monitoring came in 1988–89, when researchers Dan M. Duriscoe and Sandra L. Graban established a completely new set of forty-five 4-ha plots throughout both districts of the monument. This project was carried out at the request of the

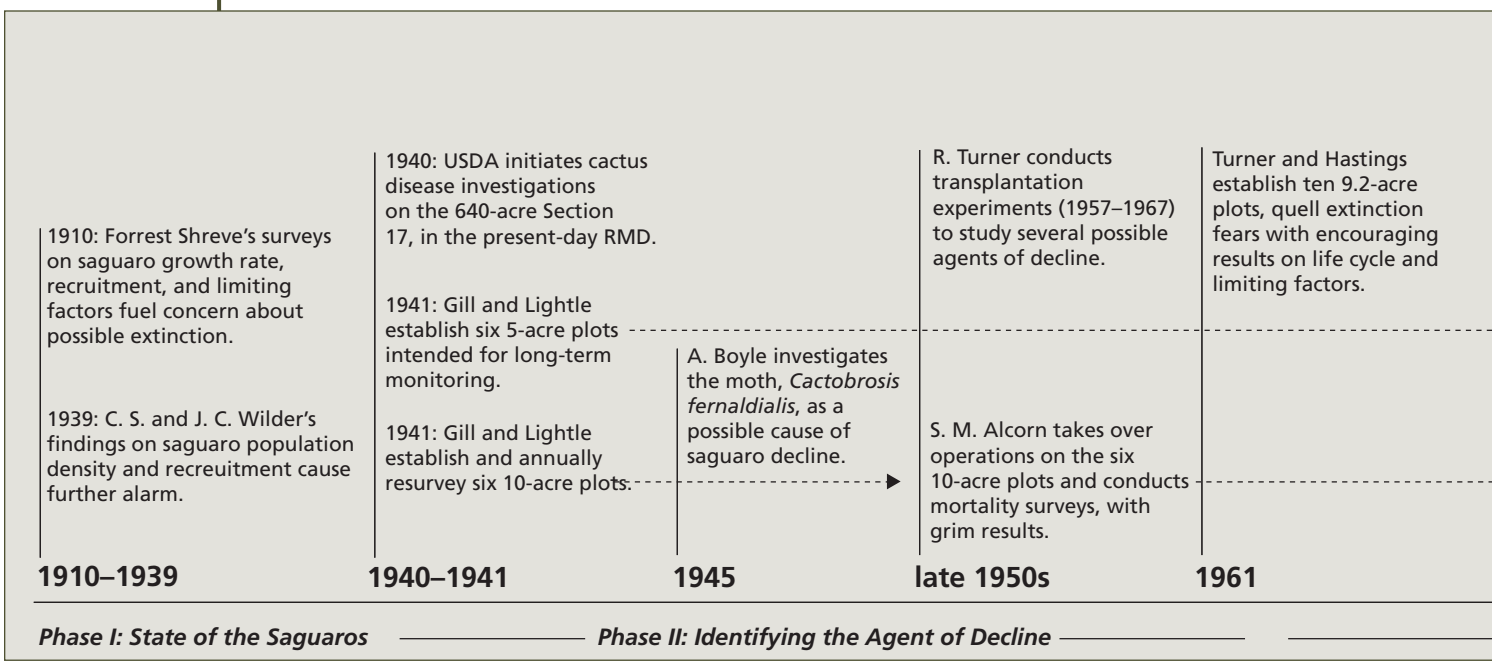


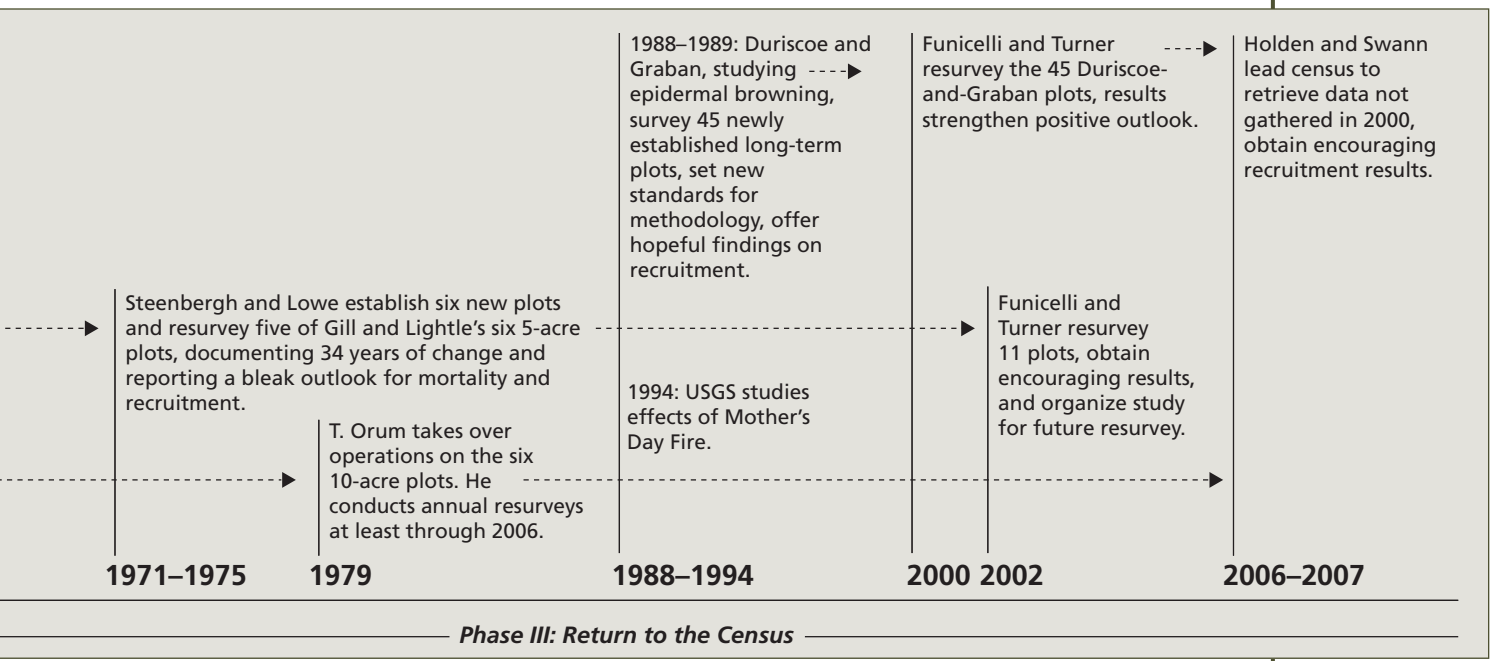
Figure 5. Timeline showing the relationships between long-term saguaro monitoring projects, Saguaro National Monument/ Saguaro National Park.

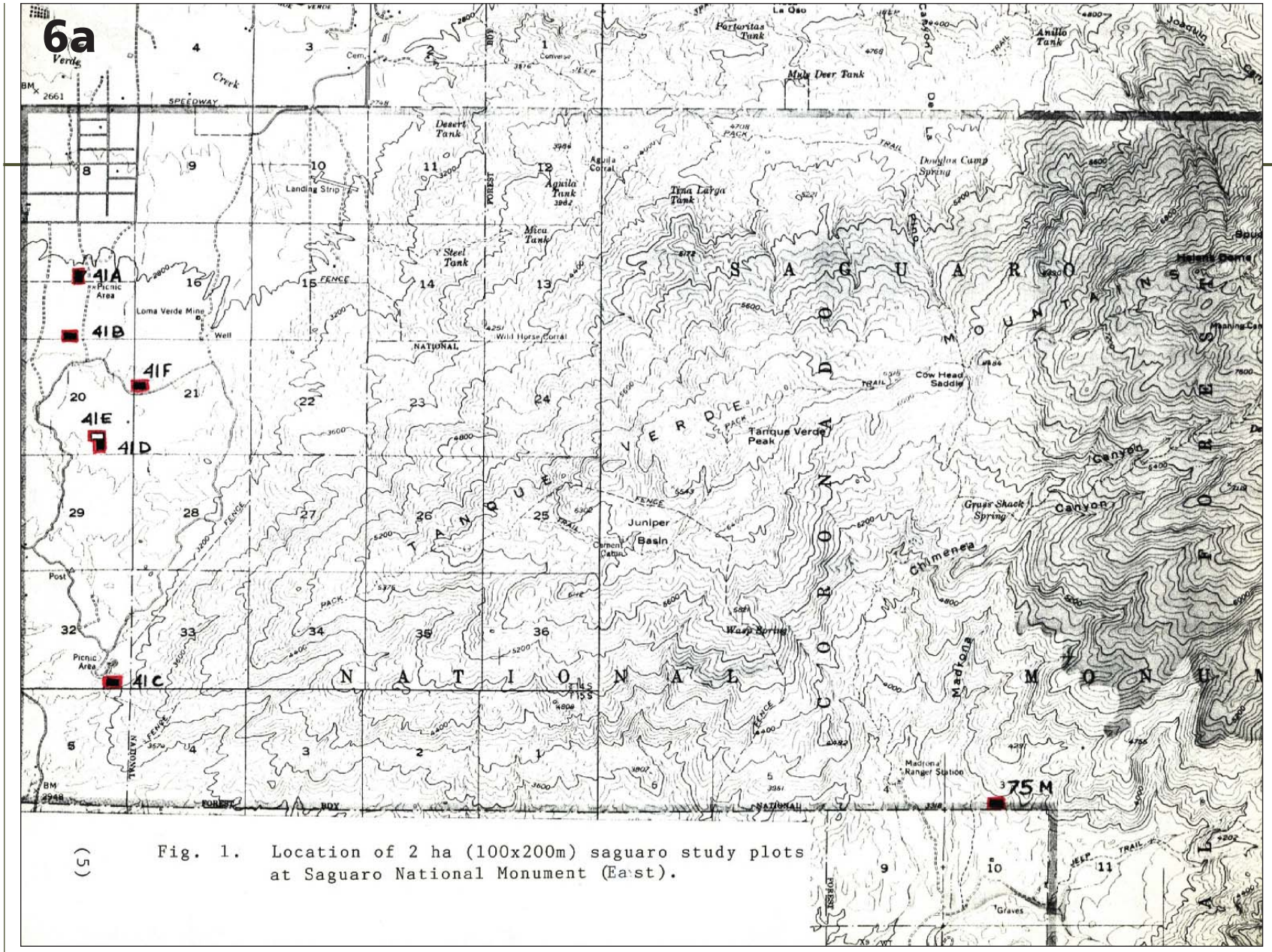
NPS's Air Quality Division, due in part to recommendations from a study done the previous year by researcher K. W. Stolte, who found that epidermal browning, a brown scale on the skin of the plant, was a widespread phenomenon, and found in greatest concentration in areas of high saguaro mortality. Stolte's recommendations for a more complete, long-term survey on the effects of epidermal browning led directly to Duriscoe and Graban's study, which began months before Turner and Hastings published the encouraging census results from their TMD and RMD plots.

The focus of the study was to "identify the extent of epidermal browning on giant saguaro cacti and to initiate long-term studies of population dynamics."[29] The survey's objective was to "establish a system of relocatable plots that represent an unbiased, independent sample of the population and of sufficient size and number to describe the condition of the population in 1989–90 in terms of incidence and severity of epidermal browning, population density and structure, and the occurrence and importance of associated plant species."[30]

In terms of the level of consistency, data analysis, and ease of repeatability, no previous study compared to that of Duriscoe and Graban, which set the stage for a new era of long-term saguaro-plot monitoring at Saguaro National Monument. Of Duriscoe and Graban's 45 plots, 25 were located in the RMD, and 20 in the TMD. The plots were selected by first dividing the environment into 45 quadrants, each containing approximately 1.5 square kilometers of "saguaro-type" habitat. One 4-ha plot was then chosen from each quadrant. This method provided for an even, arbitrary spread of plot locations throughout both districts that was also representative of the different altitude levels and terrain in which saguaros are found. The plots were two-tiered, each being 200 × 200-m (4-ha) square and containing a smaller, 10 × 10-m ecological plot, from which precise data would be recorded, not only on saguaros, but also on all vegetation species present.

In each 4-ha plot, 30 saguaros of 2 m and taller were selected for long-term monitoring, while all saguaros of 10 cm and taller were marked and tallied. Each 10 × 10-m ecological plot contained one of the selected saguaros at its center. Plots were mapped via compass, and the selected saguaros were mapped, photographed, and measured. All hand-drawn field maps were digitized using AutoCAD software.[31] In addition, Duriscoe and Graban noted "a need . . . to augment this plot system with a number of saguaro cactus mortality transects to add the





Figures 6a (above) and 6b (below). Steenbergh and Lowe's 11 plots from 1971 and 1975. Gill and Lightle's original six 5-acre plots are shown in 6a (Plot 41E was not relocated).

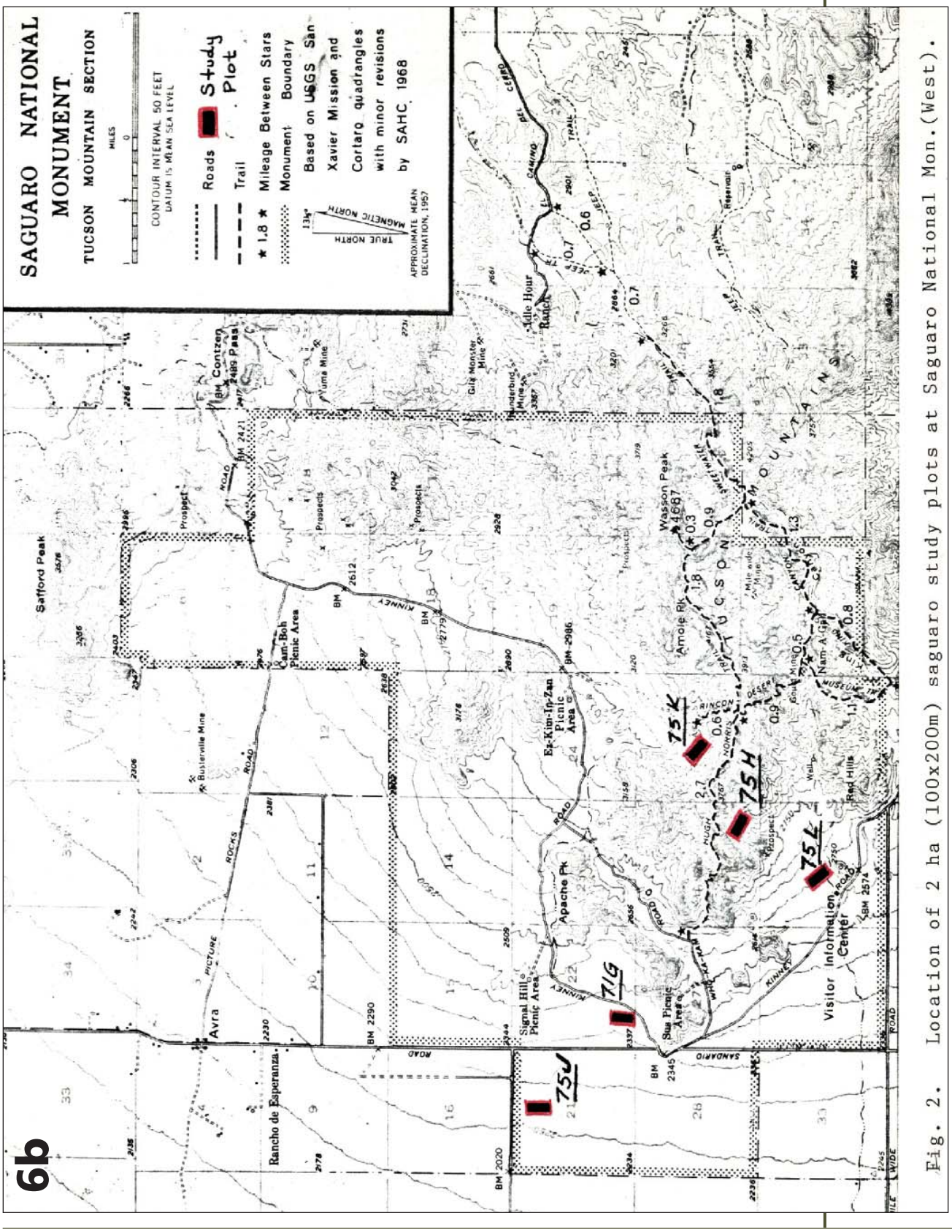


Fig. 2. Location of 2 ha (100x200m) saguaro study plots at Saguaro National Mon.(West).

dimension of a shorter time frame for observation of cactus death in relation to browning. . . . the placement of transects along washes where predominantly green saguaros are found and on adjacent bajadas where high densities of the brownest cacti reside will permit the detection of different mortality rates between brown and green groups."[32] The establishment of these six mortality transects in both districts was due, in part, to prevailing knowledge that the mature saguaro population in the Cactus Forest area was in decline. Findings were as expected: mortality of the "browner" specimens was significantly higher than that of the "greener" specimens. More information on Duriscoe and Graban's mortality transects can be found in Appendix A of Duriscoe and Graban (1991).

Duriscoe and Graban generally found that the severity of epidermal browning was positively associated with height and negatively associated with spine retention, and that the condition tended to be more severe on south-facing slopes—suggesting that the process is worsened or expedited by more direct sunlight. Another interesting find, and one that reinforced the findings of Turner and Hastings in 1989, was that an "influx of young saguaros into the Cactus Forest population of the past 10 or 20 years was documented by the finding of significant numbers of plants less than 0.5 m in height in many plots."[33] This information helped lead researchers, in the early 1990s, to conclude that the monument's saguaro population was making a surprising comeback. Figure 7 illustrates the locations of Duriscoe and Graban's 45 monitoring plots.

Orum et al.: The Saguaro Cactus Virus surveys (1966–2000)

In 1966, S. M. Alcorn and Merritt Nelson discovered a saguaro-infecting virus. The strain, named Saguaro Cactus Virus (SCV), continues to baffle researchers and park scientists to this day. The virus is difficult to detect, and Merritt and Alcorn eventually sought the advice of Dr. Zhongguo Xiong, a plant virologist at the University of Arizona. Together, the team discovered that the virus was related to Carnation Mottle Virus, a more common disease, transmitted by pollen. This led led the team to suspect that SVC was pollen-transmitted, as well.

In 1991 and 1993, Tom Orum, together with Merritt Nelson and Donna Bigelow, sampled every flowering saguaro in each of the original six 10-acre plots established by Gill and Lightle in 1941. In each plot, the team recorded a "high incidence of the virus" (T. Orum, pers. comm.). In most plots, a higher percentage of older saguaros was found to be infected compared to younger specimens (those 6–12 ft in height).

Additionally, in 1999 and 2000, as part of a Sonoran Desert-wide study, Orum and Nelson completed similar research on several of Duriscoe and Graban's plots from the 1990 epidermal-browning study. Incidence of SCV was found to be higher in the RMD than in the TMD, and the virus was again observed to be more pervasive among the older specimens. Thus, according to Orum, "The interesting question is whether the virus will be transmitted to the new generation of saguaros that are coming along and beginning to flower, or if it will die out with the older generation" (T. Orum, pers. comm.). For more information on the SCV surveys, see Milbraith and Nelson (1972), Weng and Xiong (1997), or Sun et al. (2000).

The Mother's Day Fire assessment (1994–2000)

In May 2004, the catalytic converter of a vehicle ignited a blaze in the RMD Cactus Forest area that burned approximately 1,200 acres of park land. Several park-led surveys occurred in the following years to assess the vegetation loss caused by the fire. The effort was eventually led by Todd C. Esque and Cecil Schwalbe, from the U.S. Geological Survey (USGS), and ran from 1994 to 2000. Beginning one month after the fire and lasting until February 1995, the team established transects within the burned area and selected 436 saguaros to be monitored for fire effects. In a research paper, Esque et al. (2004) stated that the "goal of setting up the transects was primarily to identify saguaros to monitor their survival over time, throughout the burned and unburned areas."[34] In May 1996, the USGS added an additional 13 transects and selected 496 saguaros from an unburned section just north of the burn area. Saguaros on both the burned and unburned sections were resurveyed annually until 2000, except for 1999. The study also surveyed associated vegetation, although the primary focus was the saguaro. Included in the burned study area was plot #13 from Duriscoe and Graban's 1988–89 survey.

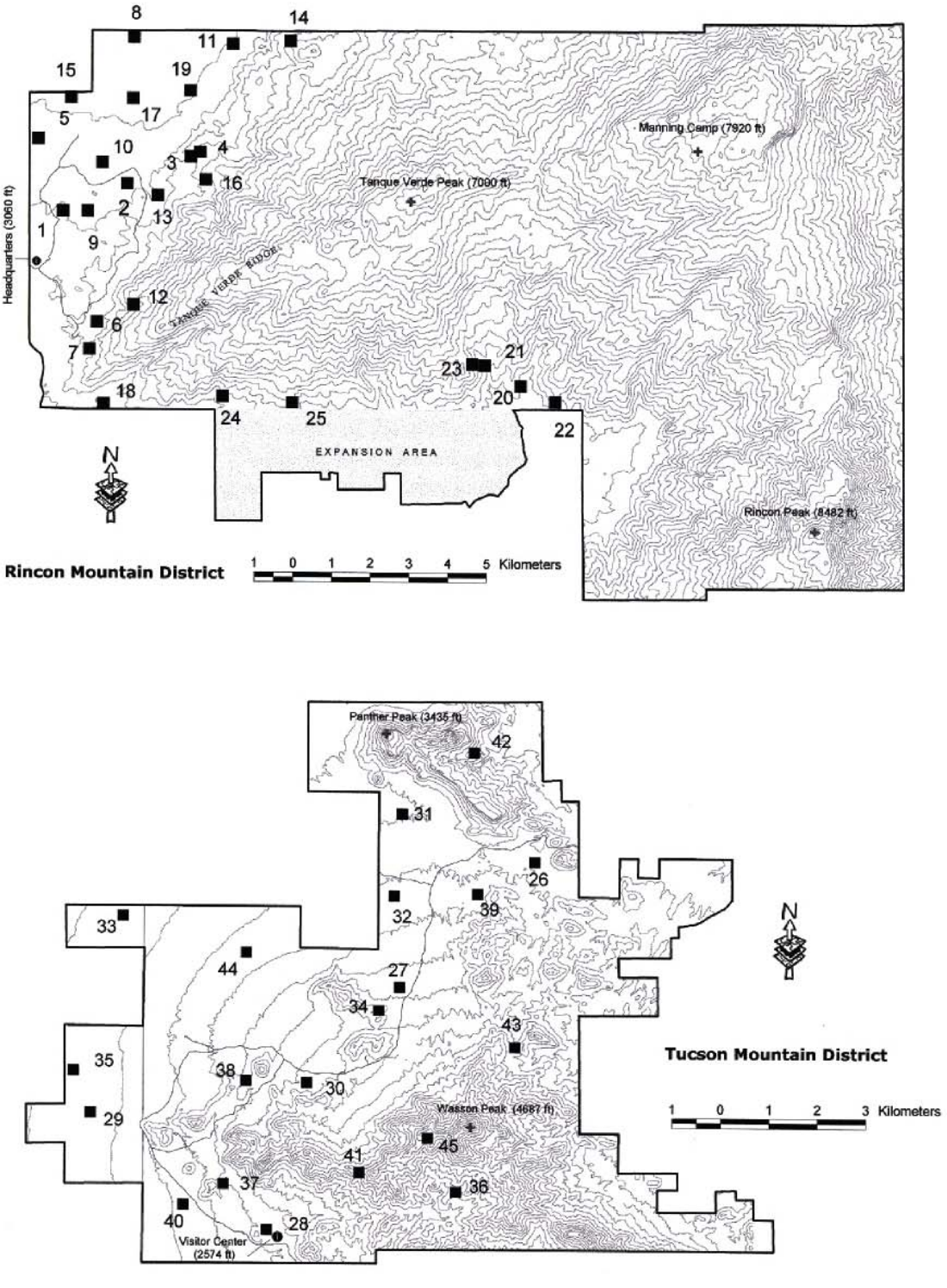


Fig. 2. Map of the Rincon Mountain District, and the Tucson Mountain District showing plot locations.

Figure 7. Duriscoe and Graban's 45 plots from 1988–89, resurveyed by Turner and Funicelli in 2000.

Results from this six-year study indicated that nearly 25% of monitored saguaros on the burned section were dead by 2000. However, the study also found that mortality on the burned section was highest in the first year and eventually tapered off, until mortality rates on both the burned and unburned sections were nearly equal by 2000.[35] The USGS has most of the data from this study, but some of the 1994 plot and transect data (original data sheets, or copies of originals, plus GPS coordinates) are in the Saguaro National Park NR-Bib master file, under "Esque, T.C. et al. 2004. Saguaros under siege: Invasive species and fire: Supplemental Data)." For more information on the Mother's Day Fire saguaro assessment, see Esque et al. (2004).

Turner and Funicelli: Resurvey of Duriscoe and Graban's 45 plots (2000)

The first resurvey of Duriscoe and Graban's 45 plots was completed in 2000, by researchers Dale S. Turner (no relation to R. Turner) and Carianne S. Funicelli. The study, sponsored in part by Canon USA, Inc., made area headlines and was broadcast on national television through a series of interviews (recordings of these interviews and news coverage of the study are available at the Western Archaeological and Conservation Center in Tucson, Arizona). Turner and Funicelli turned in two separate reports. One focused on the larger, 200 × 200-m plots (Turner and Funicelli 2000); the other focused on the smaller, 10 × 10-m plots (Funicelli et al. 2000). Condensed versions of both reports were published in October 2000 and April 2001, respectively.

Turner and Funicelli's resurvey, in 2000, used Duriscoe and Graban's study as a template for gathering information, allowing them to recover vital data that might have been lost had the resurvey not followed its predecessor so closely. The protocol and structure of the studies were, in effect, identical, except for a slight advancement in the technology used (the use of compass-and-grid orientation to locate plots and specific saguaros gave way to GPS coordinates, and digitized backups of plot maps on 5¼-inch floppy disks were replaced by CD-ROMs). Individual saguaros tagged in 1988–89 were relocated, studied, and rephotographed. Original plots were relocated and rephotographed, and precise information on vegetation growing within each 10 × 10-m ecological plot was recalculated. The end result was an astonishing collection of previously undocumented data on the effects of epidermal browning as well as saguaro growth, cohabitation, density, and recruitment. The results from 2000 confirmed those from 1988–89: percent cover of epidermal browning increased with saguaro height (and presumably age), and was most intense on south-facing slopes.

Turner and Funicelli also planned to record saguaro census data for all original forty-five 200 × 200-m plots but, for undocumented reasons, only recorded such data for 18 plots. From those 18 plots, Turner and Funicelli recorded encouraging results, with a mean saguaro increase of 32%.[36] In 2006 and 2007, volunteers and NPS personnel returned to 10 of the 27 plots not surveyed since 1988–89. Details of those 2006–2007 census are explained later in this report.

Turner and Funicelli's 2000 resurvey represented a critical 10-year period of change, coming at a time when encouraging saguaro census results had been recently presented by Turner and Hastings, Tom Orum, and Duriscoe and Graban. Fortunately, Turner and Funicelli's 2000 resurvey only strengthened these results, and helped lead to a more positive outlook on the saguaro's future. A similar resurvey of Duriscoe and Graban's original 45 plots is scheduled to be completed in 2010. For more information on Turner and Funicelli's 2000 resurvey of Duriscoe and Graban's 45 plots, see Turner and Funicelli (2000) and Funicelli et al. (2000).

Funicelli and Turner: Resurvey of Gill and Lightle's 5-acre plots (2002)

This resurvey, "Relocation and Restudy of Historic Saguaro Plots at Saguaro National Park," represented a second resurvey of Steenbergh and Lowe's 11 plots from 1971 and 1975 (including five of Gill and Lightle's original six 5-acre plots). Results from this 2002 resurvey were very different from Steenbergh and Lowe's 1975 results, which had shown an overall decline in all age classes on combined plots and attributed them to the effects of a series of catastrophic freezes (though some plots in the Cactus Forest did show increased recruitment

of young saguaros in 1975). The results of Funicelli and Turner's 2002 resurvey, however, were similar to those of their 2000 resurvey of Duriscoe and Graban's plots: saguaro recruitment was on the rise. This conclusion was reached due to the relatively high density of young saguaros (those less than 6 ft in height) discovered throughout the relocated plots.

The plots were located by using a hand-drawn map from W. F. Steenbergh, and were studied from February 2001 through May 2002. Saguaro density and recruitment data were then collected and placed in historical perspective: "The current project provides a unique opportunity to put the results of Turner and Funicelli (2000) into a longer ecological time frame through the comparison of these data with data from the 11 plots that were established in 1941, 1971, and 1975 by Gill and Lightle (1942) and Steenbergh and Lowe (1983)."[37] Funicelli and Turner's 2002 resurvey was a significant step toward organizing this specific set of plots for future study. The final report contained plot locations via GPS coordinates as well as their data in comparison to previous results. As of yet, there is no scheduled resurvey for these plots. For more information on Funicelli and Turner's 2002 resurvey, see Funicelli and Turner (2002).

Holden and Swann: Gap Census (2006–2007)

In the springs of 2006 and 2007, Saguaro National Park personnel and volunteers, led by Mark Holden and Don Swann, returned to seven plots in the TMD (plots 27, 28, 29, 32, 35, 37, and 44) and three plots in the RMD (plots 1, 9, and 20) that had not been surveyed for census data since Duriscoe and Graban's survey of 1988–89. The main purpose of the 2006–2007 census was to "fill in the gaps" left by Turner and Funicelli's 2000 resurvey. Whereas the 1988–89 and 2000 studies focused primarily on the extent of epidermal browning, the 2006–2007 census was concerned almost entirely with gathering data on saguaro density and recruitment. In addition, the 2006–2007 census intended to see how much (if any) growth had occurred across all plots (average) since 2000.

The 2006–2007 census yielded encouraging results. Young saguaros (those <.5m) had increased 157% in the surveyed TMD plots, and an astounding 542% in the surveyed RMD plots since 1990. Additionally, total saguaro density had increased 93% across the TMD plots and 217% across the RMD plots since 1990. When seedling-growth data were compared with findings from the 2000 resurvey, findings were congruent with those of past surveys. While the RMD was characterized by an increase in recruitment levels, TMD plots showed a slight decrease in average recruitment levels since 2000. For more information on the 2006–2007 census, see Ahnmark et al. (2007).

Conclusions

The history of saguaro monitoring in Saguaro National Park can be thought of as comprising three different phases (see Figure 5). These phases are by no means exclusive or rigid, but more general in nature. Each is distinct, yet all three are interwoven. Those phases are (1) the initial findings, i.e., the "state of saguaros," 1910–1939; (2) identifying the agent of decline (and gaining a better understanding of the saguaro itself) and implementing a cure, 1940–1960; and (3) ecological studies, the second round of census results, and the population surge, 1961–present.

The first phase is characterized by the Shreve and Wilder surveys that focused on saguaro population density, establishment, and recruitment. Their reports constituted the foundation of the park's saguaro monitoring, and their grim conclusions largely prompted the second category.

The initial disease investigations by the USDA and Gill and Lightle focused predominantly on the causes, spread, and cure of bacterial necrosis. Other studies centered on climatic and anthropogenic (grazing, deforestation, and air quality) factors. Also included in the second category are the Alcorn studies on the science of the saguaro itself—its respiratory and circulatory systems, germination tendencies, cell structure, and root system. This second category represents the realization of Forrest Shreve's 1910 call for a "fuller knowledge" of the saguaro.

The third and final phase is characterized by a focus on ecological studies and conserving the saguaro within its overall environment. Encouraging census results gathered by Turner

and Hastings, Orum, Duricoe and Graban, and Turner and Funicelli have all confirmed that the future of the saguaro in Saguaro National Park is looking more positive. Additionally, results from the 2006–2007 census helped confirm that saguaro recruitment and overall population density are increasing—most notably in the RMD, where fears of saguaro extinction were greatest.

Thus, despite immense changes in methodology and technology, the overriding purpose of saguaro research remains clear: to scrutinize and study the giant cactus in its respective habitats in order to better understand its nature and, therefore, provide proper and successful measures of preservation for its future.

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Natural Resource Program Center
1201 Oak Ridge Drive, Suite 150
Fort Collins, Colorado 80525

www.nature.nps.gov