Mapping a Thousand Saguaros

Using GIS and GPS technologies to carry out a large-scale inventory at the Desert Botanical Garden

Abstract

The Desert Botanical Garden (DBG) encompasses 140 acres in Phoenix, Arizona, and is home to over 4,400 desert plant species, including the iconic *Carnegiea gigantea* (saguaro). Adoption of a cloud-based, GIS-augmented plants database (www.livingcollections.org) enabled the Garden to carry out an in-depth inventory of the nearly 1,000 saguaros on garden grounds. This paper describes the methodology used to carry out the inventory as well as preliminary analyses that have been performed on the data.

The saguaros were mapped with a survey-grade GPS unit. Locations were stored in an ArcSDE geodatabase and a map service was created to synch the data with the Living Collections database. Next, volunteers equipped with iPads utilized inventory tools on the Living Collections site to navigate to and inventory each saguaro.

The inventory covered crucial horticultural management data such as plant condition and size. Additionally, height and diameter measurements for saguaros growing in natural (undeveloped) areas of the Garden will serve as a baseline dataset for biannual measurements that will help us better understand the saguaros' responses to varying climatic conditions over time.

Introduction

The Desert Botanical Garden was established in the center of the Phoenix Valley 75 years ago and has the distinction of housing one of the largest collections of *Cactaceae* (the cactus family) in the world. Keeping accurate records regarding the origin, condition, and location of each plant in our living collection is important for maintaining our museum accreditation, but more importantly, having this information adds enormous scientific value to the collection.

The Garden has a long history of mapping using various survey technologies. However, two years ago the Garden was awarded a grant from the Institute for Museum and Library Services (IMLS) to create a GIS-rooted plant records database which we now call the Living Collections Management System (LCMS). This enables the Garden, for the first time, to link precise spatial coordinates with all other plant data. The architecture of the LCMS is the result of a year and a half long collaboration between the Desert Botanical Garden and the Missouri Botanical Garden.

The Garden began by acquiring the necessary hardware and software, including a dedicated GIS server, a TopCon survey grade GPS receiver, and a plotter. ArcGIS for Desktop and Server licenses were donated to the Garden by Esri through the ArcGIS for Public Gardens program. Additionally, orthophotos were donated by the Salt River Project (a local utility company) and the Maricopa Flood Control District, and a contour dataset was provided by the Maricopa Flood Control District. Lastly, a GIS technician was

recruited to head up the creation of the Garden's geographic information system. Leveraging these resources, the Garden set out to map its living collections.

Faced with the formidable task of mapping upwards of 25,000 plants, we chose to start with the saguaro collection. The saguaro is the single most studied plant in the Sonoran Desert, however, the very long lifespan of this keystone species has made it very difficult to construct a good picture of saguaro population dynamics. Due to the many unknowns about saguaro growth rates, there is much debate at our Garden regarding the size and age structure of our collection. The most frequently asked question from visitors is "How old is that saguaro?" Past inventories have only dealt with a portion of the collection that is located in the cultivated areas of the Garden, overlooking saguaros in uncultivated preserve areas, as well as many juvenile saguaros growing wild in the cultivated areas. With these research questions in mind, we carried out a 17-month inventory of all saguaros growing on the 140-acre property. This report describes the methodologies used to collect, manage, and analyze the inventory data.

Methodology

The Living Collections Management System

The LCMS (Figure 1) was integral to the inventory. The LCMS website, livingcollections.org, allows Garden staff and the public to query the plants database and view maps of all accessioned plants at the Desert Botanical Garden and Missouri Botanical Garden. Staff have access to additional tools and editing privileges. The LCMS website and tools are designed for usage on an iPad or iPhone out in the field as well as on a desktop computer. During the saguaro inventory, we utilized a suite of these 'mobile tools', including inventory and measurement forms as well as a photo documentation tool. Through the use of login privileges, all inventory data input by staff and experienced volunteers were updated in real time in the LCMS while data input by less experienced volunteers were reviewed and approved by the GIS technician before being saved permanently to the LCMS.

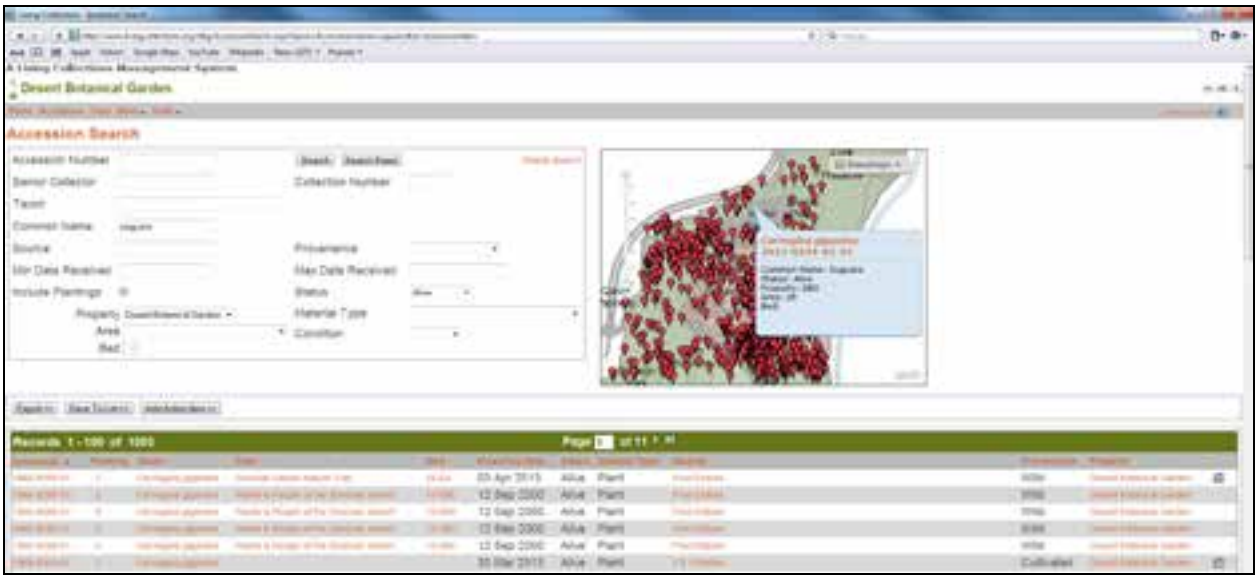

Figure 1. The Living Collections Management System website

The LCMS is comprised of a cloud-based plant records system linked to each garden's ArcSDE geodatabase by REST map services that allow the LCMS to read and write to features in the geodatabases. The ArcSDE geodatabases contain the mapped locations of plants at the Desert Botanical Garden and Missouri Botanical Garden. The LCMS draws on the geodatabase for location information (i.e., the x,y-coordinates and planting bed) for each mapped plant. Conversely, the geodatabase is updated when plants are 'unmapped' in the LCMS. These exchanges enable garden staff to edit the locations of plants in either the geodatabase or the LCMS website. The plant records database and the geodatabase are synchronized daily (Figure 2).

Figure 2. Linkages between the ArcSDE Geodatabase and the Living Collections Management System database

Inventory protocol

The saguaro inventory differed markedly from past inventories in its taxonomic focus (the saguaro species), the spatial granularity of location information (1-foot accuracy as opposed to planting bed location), and in the area covered by the inventory (the entire property rather than the cultivated

portion). This allowed us to obtain a complete picture of the status of a single species (of great interest to the Garden) in a much shorter period of time.

The inventory was divided into two phases. In the first phase, the GIS technician worked with a team of volunteers to carefully walk the Garden's 140 acres (approximately 55 cultivated and 85 in preserve), to locate and map saguaros, both cultivated and wild. A TopCon GRS-1 GPS receiver paired with an RTK receiver was used to map the plants. The GRS-1 achieves sub-centimeter accuracy under ideal conditions and consistently provides the Garden with the accuracy needed to differentiate plants that have frequently grown within two feet of each other. The spatial error inherent in mapping our plant collection, particularly those in the *Cactaceae* and *Agavaceae* families, can be almost entirely attributed to plant shape, size, growth, and the physical danger experienced by the GPS user when approaching plants with spines, thorns, and sharp leaves. During the inventory, nearly 1,000 saguaros were located. Each was mapped and those that were not already being tracked in our plants database were tagged with an accession number (a 12-digit code used to uniquely identify each plant in the living collection).

The GIS technician and a team of volunteers then carried out a full inventory of each saguaro. We recorded the following observations and measurements: status (alive or dead), condition (excellent, good, fair, or poor), protection from wildlife predation (caged or uncaged), height, diameter, and number of arms. The volunteers added additional comments at times to clarify the inventory or more fully describe particularly unique specimen. Height was measured using a laser range finder (for tall saguaros) and a tape measure (for short saguaros). Measurements can be assumed to be accurate to +/- 0.5 ft given the difficulty in obtaining measurements on steep hillsides. Diameter was measured with a set of calipers and can be assumed to be accurate to +/- 0.1 ft. The height and orientation of the diameter measurement was marked with a paint pen to facilitate future repeated measurements. The margin of error for the height measurement will make it difficult to detect changes in height in the near future for individual plants, however, the aggregate changes for the population can be found. Lastly, arms and buds (under 1 foot) were counted and a photograph was taken of each plant. Volunteers who were comfortable using iPads entered all data into the LCMS on the spot while volunteers who had difficulty viewing the screen in bright sunlight or preferred working with pen and paper, entered the data back in the office.

During this phase, very young saguaros were notoriously difficult to locate as they were often sheltered by dense brush. Also, bristling with spines, the young saguaros were perfectly camouflaged on rocky surfaces. The GIS layers that had been developed for the Garden at this point (e.g., orthophoto, paths, washes, and fences) made it possible to return to and inventory every saguaro that had been located during the initial mapping phase.

Inventory Results

The saguaro population count at the Garden stands at 978. All saguaros taller than 6 feet were certainly located; however, some saguaros under ½ foot were likely overlooked. The smallest saguaro inventoried measured 1 inch (approximately 3 years in age).

A snapshot of the inventory results is shown in Figure 3. For the analyses presented here, data was available for 921 of the 978 total saguaros.

Accession Number	Condition	Caged/Not Caged	Height (feet)	Diameter (inches)	Arm Count	Bud Count	Additional Observations	Inventory Date
1966-8304-01-1	Good	Not caged	28.2	23.7	4			3/30/2013
1976-1021-01-1	Excellent	Not caged	19.9	22.6	6	2		12/31/2012
1976-9009-01-1	Excellent	Not caged	23.7	18.5	3	3		5/13/2013
1971-0130-01-1	Good	Not caged	6.1	13.3	0	0		5/8/2013
1972-0198-01-1	Fair	Not caged	5.9	11.0	0	6		5/17/2013
1976-0079-01-1	Excellent	Not caged	16.8	14.3	0	0		1/10/2013
1976-0285-01-1	Good	Not caged	11.7	17.9	5			1/22/2013
1976-0379-01-2	Good	Not caged	18.7	19.7	11	4	Double trunk.	5/13/2013
1976-0379-01-3	Good	Not caged	11.5	14.3	0	0	Double trunk. Shorter trunk on south side measured 10.8"/13.3".	1/4/2013
1976-0379-01-4	Good	Not caged	18.7	16.6	2		Damage at bottom, constriction ring 4 feet from bottom.	4/6/2013
1976-0379-01-5	Excellent	Not caged	9.2	11.9	2		Minor damage healed.	3/16/2013
1976-0379-01-6	Excellent	Not caged	15.9	14.1	0	1		2/25/2013
1976-0379-01-7	Excellent	Not caged	10.2	13.6				3/16/2013

Figure 3. Inventory results

The distribution of measured heights is shown in Figure 4. One of the driving questions at the start of the inventory was "Is our saguaro population healthy and reproducing naturally?" Observing the spike in saguaros below 4 feet tall led to a collective sigh of relief at the Garden. However, a more accurate answer will be obtained once we have separated out the portion of the population (approximately half) that grows natively in the preserve from the portion that was transplanted and/or benefits from irrigation.

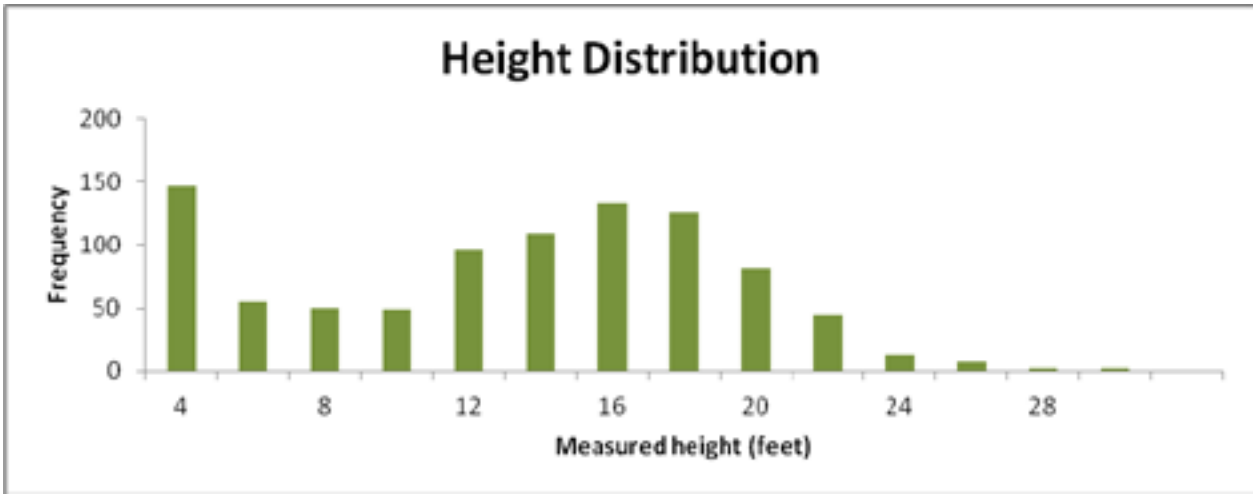

Figure 4. Distribution of heights, n=921

The height data was then used to create a 3D visualization in ArcScene (Figure 5). Where statistics failed to impress, a fly-over of the garden, passing by a forest of 25-foot saguaros interspersed with saguaros as small as 1 inch convinced staff and volunteers that there was, indeed, a sizeable population of juvenile saguaros. As these young saguaros are effectively invisible to a person walking around the Garden, this visualization of the 'saguaro landscape' was an eye-opening experience for some of the Garden's veteran volunteers.

Figure 5. A 3D visualization of the saguaro landscape at the Garden

An additional attribute (modeled age) was derived by matching our saguaro heights to height-to-age conversions that have been published for saguaro populations in other parts of the Sonoran Desert (Drezner, 2003; Steenbergh & Lowe, 1983). While these age estimates are coarse, they do provide some insight into the age structure of the population (Figure 6). The heights used to form this distribution are the average of the least and most ideal growing conditions.

Height-to-age conversion formulae are available for saguaro populations located in several different regions of the Sonoran Desert that are subject to significantly different climatic conditions. The age estimates for the Garden's saguaro collection can therefore be improved by applying the best-suited conversion to groups of saguaros based upon long-term rainfall in the Phoenix Valley as well as individual plant characteristics such as wild versus cultivated, irrigated versus rainfed, and flat terrain versus hillside.

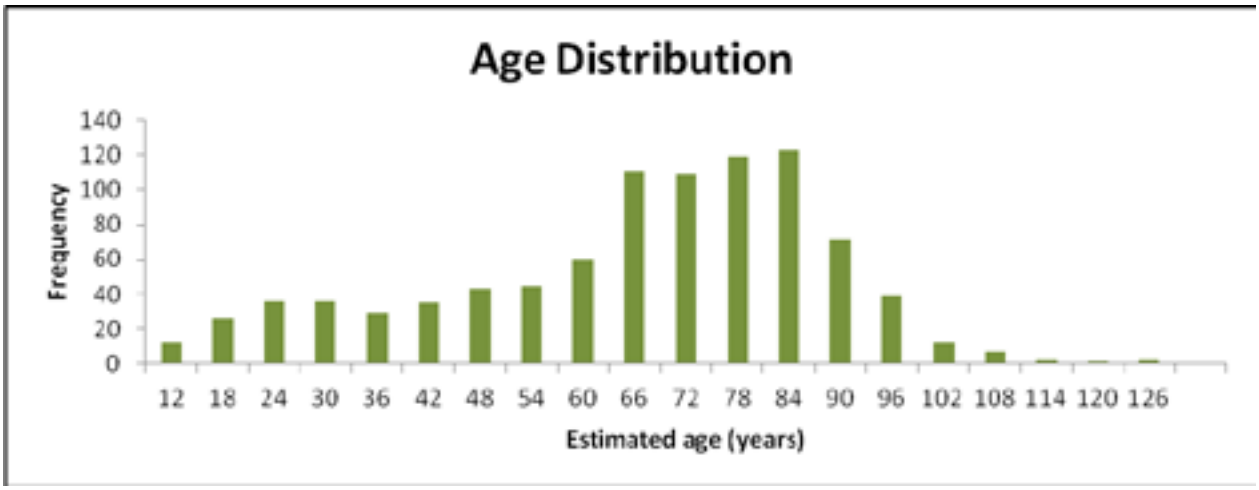

Figure 6. Age distribution, n=921

The saguaro inventory has provided a wealth of data that we hope will answer many of the questions our staff as well as our visitors have concerning individual saguaro ages and the age structure and health of the population as a whole. Some of the initial analyses have been presented here. In future years we plan to collect height and diameter measurements to gauge the growth rates and changes in diameter due to seasonal and long-term climate variation.

Some of the data collected during this inventory (e.g., condition and presence of a cage) is of immediate practical use to the Horticulture Department. Knowing the condition and presence of a cage will help prioritize the replacement of cages. Figure 7 depicts saguaros according to whether they have reached the onset of reproduction. This is estimated based on the modeled age of the saguaro and whether the saguaro has grown its first arm. The spatial distribution observed on the map leads us to wonder if there are areas of the Garden that are more conducive to the survival of young saguaros. This type of information is useful to the Horticulture staff in the long run as they are tasked with ensuring the health of our collections.

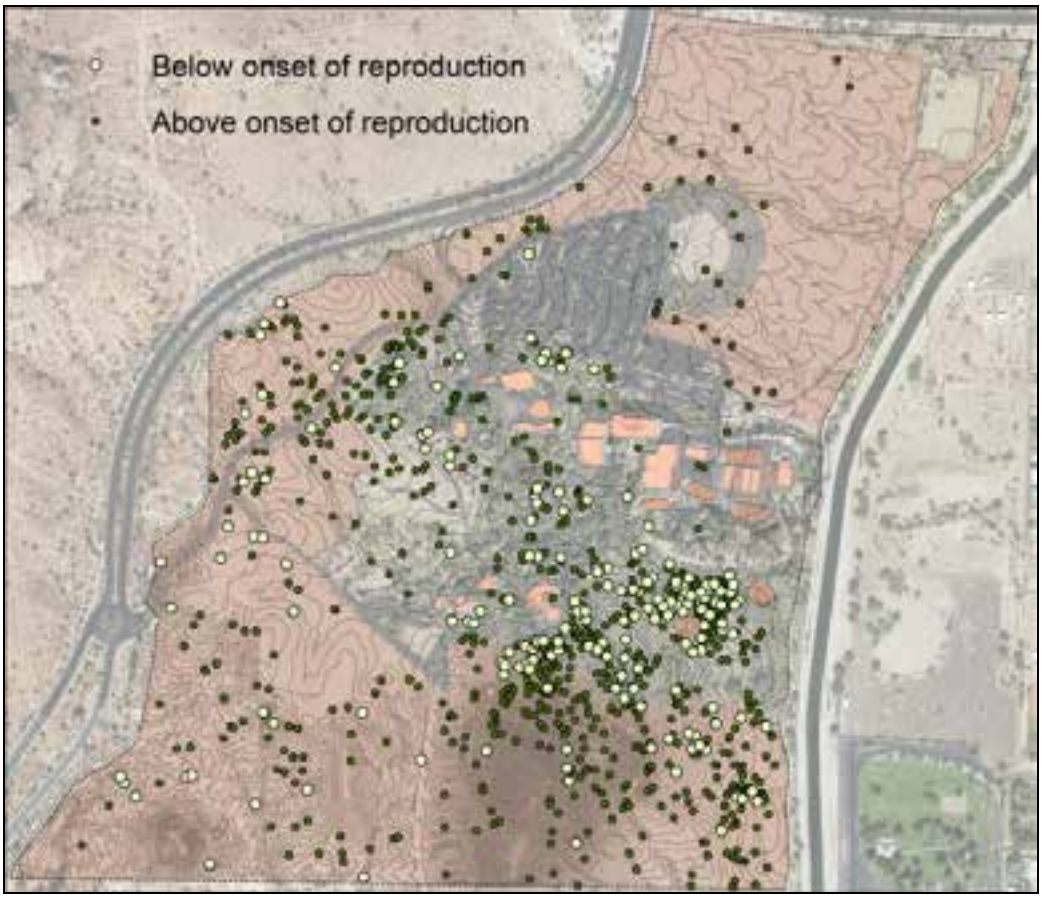

Figure 7. Saguaros grouped according to age relative to onset of reproduction

Conclusions

The Garden has always kept detailed plant records data. However, tying each record to a precise x,y-coordinate and making this information readily accessible to all of our staff and volunteers has had some unexpected and wonderful implications for how many of us carry out our work. For example, the search time has been greatly reduced to find specific plants within large planting beds. This is crucial in the Sonoran Desert where temperatures exceed 100 degrees for much of the year. The process of implementing the LCMS illuminated certain errors that existed within the original plant records database.

One of these errors is, quite by accident, searchable within the Accession Search screen of the LCMS. Searching for plants with criteria *Status* = *Dead* and *Mapping Status* = *Mapped* produced a list of plants that were listed as dead during a past inventory (frequently because they could not be located), but were evidently located and mapped this past year. In this situation the LCMS (and the process of collecting data to populate it) uncovered a systematic problem and then presented a systematic way to research and rectify it. In addition to helping us efficiently uncover and rectify errors in our plant records, the LCMS has already proven its value by facilitating much of our daily work (including plant inventories) and by making our plant records visible to the general public.

References

Drezner, T. D. (2003). Saguaro (*Carnegiea gigantea*, *Cactaceae*) age-height relationships and growth: The development of a general growth curve. *American Journal of Botany* , 911-914.

Steenbergh, W. F., & Lowe, C. H. (1983). *Ecology of the Saguaro: III.* Washington, D.C.: U.S. Department of Interior-National Park Service.