# The Influence of Soil Characteristics on Saguaro (*Carnegiea gigantea*)

# Post Wild Fire Restoration Efforts

by

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# ABSTRACT

The Cave Creek Complex fires of June and July of 2005 north of Phoenix, Arizona, U.S.A. burned 248,310 acres of Sonoran desert, primarily on the Tonto National Forest, USFS. The fires consumed multiple stands of the keystone species *Carnegiea gigantea*, the saguaro cactus. Restoration efforts in late spring 2007 involved the monitoring of 200 transplanted saguaro cacti over a two year period for overall establishment and success. Observation of local saguaro distribution suggests that soil factors might influence saguaro growth. Therefore, soil samples were collected from each transplant location and analyzed for percentage coarse fragments, texture, pH and electrical conductivity as soil collection and analysis of these variables are relatively inexpensive and expedient. Regression analysis was used to determine which, if any of these soil characteristics significantly correlated with plant growth. The results of this study found significant correlation between saguaro transplant growth and the soil variables of clay content and pH, but no correlation between saguaro growth and coarse fragment percentages or electrical conductivity.

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# Chapter 1

# INTRODUCTION

The saguaro cactus, *(Carnegiea gigantea* [Engelm.] Britt. & Rose), a distinctive, many ribbed columnar cactus ranging from the western regions of Sonora, Mexico northward thru southern Arizona, U.S.A. is a keystone species in the Sonoran Desert, providing critical resources for any Sonoran desert species consuming nectar, pollen, fruit, or cactus tissues (Fleming and Valiente-Banuet, 2002). While saguaro cacti possess many physical adaptations that allow their establishment and success in the harsh conditions of the Sonoran Desert (Niering, Whittaker, and Lowe, 1963; Smith, Dinnen-Zopfy, and Nobel, 1984; Darling, 1989; Nobel, 1978; McDougal and Working, 1921; Spalding, 1905), they are poorly adapted to the stresses of wild land fire events and suffer high mortality rates (McLaughlin and Bowers, 1982; Rogers, 1985). The Cave Creek Complex fire events of the summer of 2005 in the Tonto National Forest northeast of Cave Creek, Arizona, U.S.A. burned 248,310 acres of Sonoran desert and decimated stands of old growth saguaro. Restoration efforts following that fire beginning in the spring of 2007 provided an opportunity to examine soil variables that might significantly influence saguaro transplant efforts. Previous studies suggested that saguaro seedling and transplant success may be influenced by soil characteristics (Steenbergh and Lowe, 1969). The relative ease of collecting and analyzing the soil characteristics of coarse fragment percentages, texture, electrical conductivity and pH makes these soil attributes attractive focus points for further scrutiny. In the event of a meaningful correlation between any of these features and saguaro growth, this information could prove valuable for land managers in the selection of future saguaro transplant locations.

# Chapter 2

# LITERATURE REVIEW

## ***Carnegiea gigantea***

*Carnegiea gigantea,* commonly known as the saguaro cactus, is the largest succulent plant in the United States with commonly observed heights of 12 meters (m) or more (Figure 1). This distinctive, many ribbed columnar cactus ranges from the western regions of Sonora, Mexico northward through southern Arizona. Although the plant's tolerance of colder temperatures allows it the northernmost range among the columnar cactus of the Sonoran Desert, it is ultimately the combination of extreme freezing events and altitude which limits its northern range. Saguaros grow from sea level up to 1066 m (exceptionally 1370 m) in well-drained soil.

The saguaro flowers mostly from the stem tips in May and June with white blossoms having an odor likened to ripe melon (Kearney, Peebles, Howell, and McClintock, 1979). The flowers open at night and remain open until mid-afternoon of the next day (Figure 2). Saguaros appear to time their flowering and fruiting periods during the driest and hottest periods of the summer, preceding the monsoon precipitation events of mid-summer.

The saguaro cactus life span averages 125 to 175 years with a potential of nearly three centuries (Pierson and Turner, 1998) while having extraordinarily slow growth rates. In the Tucson Mountains, which average 36 cm of annual rainfall, ten years of growth equal 3.8 cm; thirty years growth equals 61 cm (Arizona-Sonora Desert Museum, 2000).

**Figure 1. *Carnegiea gigantea* in Tonto National Forest, Arizona, U.S.A., July 2007.**

**Figure 2. Saguaro blossom open midday; Tonto National Forest, U.S.A. June 2007.**

On average, growth increases quickly with size to a maximum when the plants reach a height of 2 to 4 meters, then declines until a second inflection point at heights around 6 to 7 meters, followed by a more constant and gradual rate of decrease as the plant ages. The growth rate up to two meters is a function of the increasing photosynthetic surface area and water storage capacity as the plant size escalates. When flowering begins at around two meters, diversion of resources towards this effort slows annual growth. The second growth surge correlates with the appearance and growth of branches (Pierson and Turner, 1998), when the cactus is about 5 to 7 meters tall (McAuliffe and Janzen, 1986).

The saguaro is a considered a keystone resource for any Sonoran desert animal species consuming nectar, pollen, fruit, or cactus tissues (Fleming and Valiente-Banuet, 2002).

The flowering season of the saguaro makes it especially influential for Sonoran wildlife, providing essential water, energy and nutrients (Wolf and Rio, 2003). Recesses in saguaro trunks provide critical habitat for avian secondary cavity nesters such as the elf owl (*Micrathene whitneyi*; Goad and Mannan, 1987), western screech owl (*Otus kennicottii*; Hardy and Morrison, 2000), gila woodpecker (*Centurus uropygialis*), Mearns gilded flicker (*Colaptes chrysoides mearnsi*; Gilman, 1915), purple martin (*Progne subis Hesperia*; Stutchbury, 1991), desert white-winged dove (*Zenaida asiatica mearnsii*), and mourning dove (*Zenaida macroura*; Wolf, Martíbez, and Babson, 2002).

## Seedling/Transplant Success

Saguaro seedlings normally experience high mortality rates during the first years of life. Factors influencing seedling success or failure include climatic variables such as freezing, drought, and sunlight, microhabitat features affecting shading and soil surface temperatures, erosion of soil and predation of both seeds and seedlings by rodents, insects and birds. A 1965 study by Steenbergh and Lowe (1969) in the Saguaro National Monument monitored seedlings at weekly to bi-weekly intervals for size, color, development and general appearance, as well as evidence of rodent or insect disturbance. Climatic factors included drought, erosion, and frost, and were relatively affected by differences in exposure, slope, soil, and topography. Saguaro seedlings over a few weeks old were most often found in proximity to a ‘nurse plant’ or other shade-providing object. Although seed germination was lower in rockier habitats, seedling survival was higher in those habitats (Steenbergh and Lowe, 1969).

Turner, Alcorn, Olin, and Booth (1966) confirmed the critical nature of a shading ('nurse') plant. Of an initial planting of 2400 seedlings, mortality among one group of 1200 unshaded plants reached 100% within one year compared with 65% mortality among a group of 1200 shaded plants. Mortality rates varied with other treatment combinations, for example, darker soils experiencing lower survivor rates and lighter soils with higher numbers of seedlings surviving. Irrigation did not enhance survival among transplants growing under the most favorable conditions; rainfall alone provided sufficient moisture (Turner et al, 1966).

A 1966 saguaro transplant study focused on the influence of direct sunlight, soil albedo and shading on seedling success. Nine hundred seedlings were greenhouse raised and then transplanted into study plots at the Southwest Desert Biology Station near Superior, Arizona at an elevation of 700 m. Seedlings were placed on plots with black, white, and natural colored surfaces, both shaded and unshaded, and soil surface temperatures and cacti internal temperatures were recorded. While shading significantly affected the survival of the seedlings, albedo did not, although it significantly affected the internal temperatures, reinforcing the significance of the shading influence of a nurse plant on seedling success (Despain, 1974).

Predation on seedling transplant efforts can be considerable, as well (Steenburgh and Lowe, 1969). A 1957 Saguaro National Monument transplant experiment utilized 800 caged transplants to exclude predation from rodents and 800 uncaged transplants. After initially planting 800 5-cm tall caged saguaros, 12 % remained after one year and there was 2% survivorship after five years. When the 800 smaller 5-cm cacti were not protected by cages, only 26 survivors were observed after 3 months and there was 100 % mortality after one year (Turner, Alcorn, and Olin, 1969).

## Saguaro Adaptations

Saguaro cacti are specifically adapted for the harsh conditions of the Sonoran desert, with summer air temperatures reaching 45 °C or more and ground surface temperatures exceeding 70 °C (Franco and Nobel, 1989).  The epidermis and hypodermis thickness of the plant is nearly 1 mm in thickness with ten cell layers, permitting absorption of much of the photosynthetically active radiation (PAR) and lessening the heat load on the plant (Darling, 1989). Heat dissipation is reduced somewhat by the distinctive cylindrical shape of the saguaro with few or no branches, giving rise to a small surface to volume ratio (Niering et al, 1963).  Saguaro are CAM photosynthesizers (Smith et al, 1984), cooling little during the day and withstanding internal tissue temperatures up to 65°C, well above the surrounding air temperatures (McDougal and Working, 1921). The saguaro's distinctive spines help reduce diurnal temperature extremes (Nobel, 1978) and the plant's accordion-like ribbing with spines exclusively on the ridges allows expansion and contraction of the plant as water resources become available (Spalding, 1905). Nurse plant associations favor seedling establishment by reducing PAR as well as soil and ambient temperature extremes (Franco and Nobel, 1989), providing shade (Turner, 1966), and supplying nutrients to the soil (Franco-Pizana, Fulbright, Gardiner, and Tipton, 1996).

## Wildfire Effects on Saguaro

Despite the physiological features favoring the saguaro's establishment and success in the Sonoran desert, the plants are poorly adapted to wildfire events, suffering high mortality rates among both mature and seedling individuals (McLaughlin and Bowers, 1982; Rogers, 1985). The Cave Creek Complex Fire event of 2005 supported this belief with high mortality rates observed among existing saguaro stands and provided an opportunity to study post wild fire saguaro restoration efforts, which are infrequently discussed in the existing scientific literature. Additionally, saguaro transplant efforts have shown little focus on the soil coarse fragment levels, texture, pH, or electrical conductivity, and the possible correlation of these variables to soil fertility and saguaro transplant success.

## Soil Variables

Examination of soil coarse fragment percentages may aid in identifying suitable locations for saguaro germination and seedling success. Rocky habitats with less vegetative cover and coarser textured soil have been observed to provide fewer favorable germination sites, but support higher survival rates for the saguaro seedlings that do germinate in these locations (Steenbergh and Lowe, 1969). Soil texture influences soil water depletion (SWD), stem water potential (SWP), and soil field water capacity (Jabro, Evans, Kim, and Iversen, 2009). Soil texture can influence soil organic matter protection, cation exchange capacity, nutrient diffusion rate (Rodriquez, Duran, Fernandez-Palacios, and Gallardo, 2009), as well as germination and survival of plant seedlings (Valdes-Rodriguez, Ofelia, Sanchez-Sanchez, and Perez-Vazquez, 2013). Saguaro populations in the Organ Pipe Cactus National Monument reached greatest densities on upper bajadas and flats with coarse granitically textured derived alluvial soils (Parker, 1988).

Soil texture also highly influences electrical conductivity (Luck, Ruehlmann, and Kirchmann, 2011). Electrical conductivity is a measure of the salinity of soil and is a major indicator of soil health, affecting crop yields, suitability, nutrient availability and soil microorganism activity (USDA, 2012). Electrical conductivity has been associated with soil fertility (Officer et al, 2004) and higher concentrations of nutrients.

Soil pH is a measure of the acidity or alkalinity in a soil, also called soil reaction (USDA, 1998). Soil pH influences the solubility and availability of soil nutrients and affects the activity of microorganisms that break down organic matter and influence chemical transformations in the soil. Soil pH has optimal ranges for specific plant species; a pH range of 6 to 7 is usually best for plant growth as the majority of plant nutrients are readily available in this range, although there are some exceptions (USDA, 1998). An examination of the soil pH from the samples taken from the canopy of each nurse plant could show correlation between pH levels and cactus growth.

# Chapter 3

# STUDY AREA

On June 21, 2005 at 4:45 p.m. lightning initiated the first of the Cave Creek Complex (CCC) fires north of Phoenix, Arizona; eventually burning 248,310 acres (100,488 hectares) with an estimated cost of over $16,471,000 (USDA, 2005). The CCC fire is to date, the third largest in Arizona's history after the Wallow fire of June 2011 and the Rodeo-Chediski fire of June 2002. The fires burned through step terrain consuming oak, grass, chaparral brush vegetation types and stands of saguaro cacti *Carnegiea gigantea* (USDA, 2005). Restoration efforts conducted by the Cave Creek District of Tonto National Forest were initiated in the spring of 2007. Potential site selection for the transplant efforts began in February of 2007. In the final analysis two sites were selected: just north of the Seven Springs Road and north east of the Mistress Mine ('Mistress' site), and the Bartlett Road site furthest east of the Camp Creek wash ('Rolls' site) approximately 6.4 kilometers (km) southeast of the Mistress site. Two hundred total saguaros were transplanted with 100 cacti each in these two locations and monitored over a two year study interval for transplant growth and establishment success. Both locations exhibited southern aspects, with observed variation between southeastern, southern, and southwestern aspects. Highly visible saguaro mortality was apparent at both the Mistress (Figure 3) and Rolls site (Figure 4), confirming that historically these areas had supported successful stands of saguaro.

Rolls site transplants were located from 911 m to 930 m in elevation over an east-west span of 275 m, from (33°51'33"N by 111°46'20"W to the eastern border of the site: 33°51'38"N by 111°46'11"W). Mistress site transplants were located from 1019 m to

1074 m in elevation over a span of 675 m (33°54'3"N by 111°49'25"W to 33°53'54"N by 111°49'1"W).

**Figure 3. Mistress Transplant Site, Tonto National Forest, U.S.A. March 2007**

**Figure 4. Rolls Transplant Site, Tonto National Forest, U.S.A. March 2007**

# Chapter 4

# MATERIALS AND METHODS

## Field Data Collection

Transplanting efforts began in April of 2007 in the areas of the Tonto National Forest affected by the CCC fires of 2005. Two hundred transplants were placed in two study sites of 100 individuals each. Transplants fell into two size classes: 100 cacti were about 5 to 6 cm; 100 were larger: from about 20 to 60 cm at planting time. Nurse plants were determined to be the catclaw acacia, *Acacia greggii*, for all study cacti as this was the most common potential nurse plant species at the two study sites. All transplanted cacti were located at the edge of the *Acacia greggii* canopy, on the uphill (northern) perimeter of the nurse plant. Growth was monitored for two years with repeated measures of height and girth taken every six weeks as logistics permitted for each individual. Measurements were taken with a 1 m field caliper, using a pre-located 30 cm section of iron rebar driven into the ground next to each transplant as a foundation for baseline measurements. Wired to each section of iron rebar was an aluminum numerical identification tag to allow re-location and correct identification of each individual cactus.

Soil samples of between 1 to 2 kg were collected from each transplant location, midway between the transplant cactus and the center of the nurse plant to a depth of about 10 cm. Soil was transferred to the laboratory in plastic bags which were left open to allow the samples to air dry. Samples were later analyzed for percentage of coarse fragments, texture, electrical conductivity, and pH.

## Coarse Fragment

Soil samples were initially weighed using a GF-1200 Analytical balance with a 1210 gram maximum load and sample masses recorded.  Samples were then sieved through a U.S.A. Standard Sieve Series sieve no. 10 with 2.00 mm openings.  Large aggregates were broken with a rubber flask stopper, sifted material was then re-weighed, and the sifted soil masses recorded.  Coarse fragments percentages were calculated from these measurements by:

$$(\text{Initial soil sample mass}) / (\text{sifted soil sample mass}) \text{ X } 100$$

## Soil Texture

Sifted soil was subsampled (two per initial soil sample) at approximately 10 grams each, masses recorded and samples oven dried for 24 hours at 110 degrees Celsius (C°) in a Fisher Scientific® IsoTemp Oven model# 651G.  After removal from the oven samples were placed in a desiccator for a minimum of 30 minutes to prevent the sample from adsorbing moisture from the air as they cooled.  Samples were then weighed again and a soil moisture correction factor was calculated as follows:

$$\text{Soil Moisture Correction Factor} = (\text{dry weight}) / (\text{moist weight})$$

To convert the moist soil weight in the lab analysis to dry weight:

$$\text{Dry Weight} = (\text{moist weight}) / (\text{soil moisture correction factor})$$

The Bouyoucos (1962) hydrometer method was used to determine soil texture using the soil texture classes of the USDA system (USDA, 2013).  Fifty gram (g) soil samples were mixed with ½ of a mixing cup of distilled water and 10 mL of a 1 N sodium hexametaphosphate solution for 5 minutes, then transferred to a settling cylinder, filled to 1 liter with distilled water and vigorously stirred. The 1 N sodium hexametaphosphate dispersing solution was prepared by dissolving 35.7 g technical grade sodium hexametaphosphate ($NaPO_3$) and 7.9 g sodium carbonate ($Na_2CO_3$) in about 900 mL deionized water. The solution pH was then adjusted to 8.3 with additional sodium carbonate and the final volume brought up to 1000 mL.

After vigorously stirring the 1 L soil/dispersant solution, with an ASTM Soil Hydrometer, hydrometer readings (grams/liter or g/L) and soil solution temperatures were then taken at 40 seconds and again at 2 hours. This data was subsequently used to calculate percent sand, clay, and silt by the following procedure:

The hydrometer was initially calibrated by the manufacturer at 20 degrees C. Hydrometer readings must be corrected for variations in temperature because the viscosity of water, and somewhat to a lesser degree, the density of water changes as the temperature changes. To correct the hydrometer readings for temperature, 0.36 gram/liter was added for every 1 degree C above 20 degrees C; 0.36 gram/liter was subtracted for every 1° C below 20° C. Once the oven-dry soil weight was calculated using the soil moisture correction factor and the hydrometer readings were corrected for temperature, percent sand, silt, and clay were determined as follows:

**% clay** = 2-hour hydrometer reading X 100/Oven-dry Soil Weight

**% silt plus clay** = 40-second hydrometer reading X 100/ Oven-dry Soil Weight

**% sand** = 100 - % silt plus clay.

Each cactus's soil sample was subsampled and the texture analysis run on two trials, with the resulting texture percentage data averaged.

### Soil pH and Electrical Conductivity

Soil pH and electrical conductivity data were developed as follows:

Distilled water was mixed with 30 grams of sifted soil in a 250 mL beaker until a stable soil paste was obtained.  Paste samples were allowed to sit for a minimum of 30 minutes to permit saturation. After the 30 minute saturation period was complete, the paste suspension was stirred again and a pH measurement taken with an Accumet® portable AP115 pH/ORP meter.  The pH electrode was immersed directly into the saturated paste, swirled gently to achieve good electrode contact, and the pH value read and recorded. The pH meter was initially calibrated before each day's experimental trials and hourly thereafter throughout the day's trials to maintain accuracy.

A 250 mL Erlenmeyer vacuum flask was then fitted with a vacuum hose attached to the side port, a small Buchner funnel inserted into the flask opening, and the vacuum hose connected to a vacuum source.  Filter paper was placed into the Buchner funnel, moistened, and the soil suspension was transferred with a metal spatula from the 250 mL beaker into the Buchner funnel.  The vacuum was turned on and the soil paste allowed to filter until the soil paste cracked and the vacuum seal was broken (this was indicated by a hissing noise as the soil suspension dried). The vacuum was turned off and the stopper, funnel, and remaining soil were removed from the flask. The collected solution was transferred from the 250 mL Erlenmeyer side-arm flask to a large test tube. The solution volume was not important, only that there was enough filtrate (10-12 mL) to cover the E.C. probe by at least 1 cm. An Oakton® RS 232 Conductivity meter was used for this procedure. The E.C. probe was calibrated per the unit's instruction manual using pre-determined standards of potassium chloride solutions. Once the E.C. meter was calibrated, the probe was rinsed with clean distilled water and placed into the test tube of collected soil filtrate. Readings were taken once the measurement had stabilized. Agitation of the test tube dislodged any air bubbles and helped maintain heterogeneity of the solution readings. The E.C. meter was re-calibrated hourly to ensure accuracy of the readings.

## Statistical Analysis

Regression analysis was conducted using the R® statistical software package. The dependent variable was selected as growth, which represented the total change in cactus height calculated from the initial transplant value measured subtracted from the final measurement. Independent variables were selected as coarse fragment, clay, which was extracted from the texture data as most likely to influence growth, EC, representing electrical conductivity, and pH. Models were run with the dependent variables considered individually and with all combinations of interactions of the variables. I then utilized IBM SPSS Statistics Data software® to analyze the variables for normality using the Kolmogorov-Smirnov and Shapiro-Wilk normality tests and created additional linear regression models with mathematically transformed variables to correct for deviations from normality.

# Chapter 5

# RESULTS

The saguaro in our study experienced considerable stress during the two year study interval from excessive heat, water loss, and predation. Initial planting dates of March 29 (Rolls site) and April 6, 2007 (Mistress site) subjected the cacti to the beginning of summer months experiencing the highest annual temperatures while simultaneously depriving the transplants of vital moisture in the weeks preceding the summer monsoon events of late June and early July. Observed mortality rates were highest during these weeks of May and June among the smallest (<10 cm) transplants, with all the larger cacti surviving. Final counts of mortality due to visible desiccation (Figure 5) were at 42 transplants of the 200 initial cacti, or 21%.

Predation also factored in heavily on the smaller (<10 cm) cacti (Figure 6), with final observed numbers at 15 total transplants of 200, or 7.5% (Table 1). Finally, during the dimensional data collection period transplants would be frequently missing from one measure date to the next, with no visible indication of the initiating cause: 10 missing cacti of the 200 initial transplants, or 5% (Table 1).

**Table 1. Observed saguaro transplant mortality**

| | **Total** | **Rolls Site** | **Mistress Site** |
|---|---|---|---|
| Desiccated | 42 | 17 | 25 |
| Predation | 15 | 14 | 1 |
| Missing | 10 | 7 | 3 |

**Figure 5. Observable desiccation of <10 cm. saguaro transplant at the Mistress planting site. Tonto National Forest, U.S.A. December 2007.**

**Figure 6. Predation observed on <10 cm. saguaro transplant at the Rolls planting location September 2008.**

Growth over the two year period varied considerably from a minimum of 1 cm to a maximum of 15 cm among the survivors. The mean value of observed growth among all transplants was 2.8 cm with a standard deviation of 3.4 cm.

Clay percentages varied from a minimum of 6.5% to a maximum of 23.2% with a mean value of 13.3%. Coarse fragment percentages ranged from 17.2% to 70.2% with a mean value of 48.1%. Soil pH values ranged from minimum of 5.42 to 7.74 at the maximum, and a mean pH value of 6.56. Electrical conductivity values ranged from a minimum of 111 µS/cm to a maximum value of 5040 microSiemens per centimeter (µS/cm) with a reported mean value of 683.6 µS/cm.

**Table 2. Growth and soil variable ranges**

| | **Minimum** | **Maximum** | **Mean** |
|---|---|---|---|
| **Growth (cm)** | -4.0 | 15.0 | 2.8 |
| **Clay (%)** | 6.5 | 23.2 | 13.3 |
| **Coarse Frag. (%)** | 17.2 | 70.2 | 48.1 |
| **pH** | 5.4 | 7.7 | 6.6 |
| **EC (µS/cm)** | 5040 | 111 | 683.6 |

**Table 3. Growth and soil data per study site**

| | Mistress Site | | | Rolls Site | | |
|---|---|---|---|---|---|---|
| | **Mean** | **Minimum** | **Maximum** | **Mean** | **Minimum** | **Maximum** |
| **Growth (cm)** | 2.2 | -4.0 | 11.0 | 5.2 | -4.0 | 15.0 |
| **Clay (%)** | 15.4 | 7.5 | 23.2 | 11.4 | 6.5 | 19.6 |
| **Coarse fragments (%)** | 47.9 | 17.2 | 68.5 | 48.0 | 26.0 | 70.2 |
| **pH** | 6.7 | 5.4 | 7.7 | 7.0 | 6.2 | 7.7 |
| **EC (µS/cm)** | 833.0 | 186.0 | 5040.0 | 493.0 | 111.0 | 2225.0 |

Cacti growth and soil data per study site (Table 3) reveals greater average growth for the Rolls site with a mean value of 5.2 cm, clay content was higher at the Mistress site with a mean percentage of 15.4%, and pH varied slightly with Rolls site mean value of 6.7 and Mistress site mean value of 7.0. The greatest range occurred in the EC data with a Rolls mean value of 833 µS/cm and Mistress site mean value of 493 µS/cm. The Mistress site maximum EC value reflected nearly twice the EC maximum level at the Rolls site. From the initial regression analysis models conducted with the R® statistical software, there was no statistical significance between any of the soil variables tested and saguaro transplant growth over the two year period of the study. Soil variables modeled individually yielded the statistical values shown in Table 4.

**Table 4. Output for regression model of additive individual soil variables**

| | Estimate | Std. Error | t value | Pr (> \| t \| ) |
|---|---|---|---|---|
| Clay | -0.4178674 | 7.2262471 | -0.058 | .0954 |
| C. Fragment | -0.1310901 | 0.0932201 | -1.406 | 0.375 |
| pH | 0.8833021 | 0.9274374 | 0.952 | 0.342 |
| EC | 0.0007544 | 0.0005808 | 1.299 | 0.196 |

This model produced a residual standard error of 4.745 on 194 degrees of freedom with a multiple R-squared value of 0.02606 and an adjusted R-squared value of 0.005976. None of the variables yielded ‘t’ values in the significant range of less than 0.05.

Table 5 summarizes the second model processed in which all interactions between variables were considered. The table includes only the variables or interactions that yielded the lowest ‘t’ values, none of which had values less than 0.05. Clay yielded the lowest ‘t’ value at 0.0954, electrical conductivity at 0.196, and coarse fragments and pH at the highest ‘t’ values of 0.375 and 0.342, respectively.

This model (Table 5) generated a residual standard error of 4.702 on 183 degrees of freedom with a multiple R-squared value of 0.09776 and an adjusted R-squared value of 0.0238. None of the variables yielded ‘t’ values in the significant range lower than 0.05. The most significant interactions appear to be of coarse fragments and EC at 0.0531, coarse fragments, pH, and EC at 0.0541, and clay, coarse fragments, and EC at 0.0561.

**Table 5. Output for regression model of interactions of all soil variables**

| | Estimate | Standard Error | ‘t’ value | Pr (> \| t \| ) |
|---|---|---|---|---|
| EC | -3.976e-01 | 2.206e-01 | -1.803 | 0.0731 |
| Clay:EC | 2.438e-02 | 1.390e-02 | 1.754 | 0.0811 |
| C. frag.:EC | 1.057e-02 | 5.432e-03 | 1.946 | 0.0531 |
| pH:EC | 6.149e-02 | 3.487e-02 | 1.763 | 0.0795 |
| Clay:C.frag:EC | -6.355e-04 | 3.305e-04 | -1.923 | 0.0561 |
| Clay:pH:EC | -3.815e-03 | 2.250e-03 | -1.696 | 0.0916 |
| C.frag:pH:EC | -1.639e-03 | 8.456e-04 | -1.939 | 0.0541 |

The variables and interactions range higher from there with ‘t’ values of 0.0731 for EC, 0.0795 for the interaction of pH and EC, 0.0811 for the interaction of clay and EC, and 0.0916 for the interaction of clay, pH, and EC.

After these initial exploratory analyses, I selectively removed data that fell into the categories of ‘predation’ or ‘missing’, as it is logical that predation would be random and independent of any soil influences. I then assessed normality using IBM SPSS Statistics Data software® by creating individual descriptive statistical menus and reviewing the Kolmogorov-Smirnov and Shapiro-Wilk normality test results, but specifically focused on the Kolmogorov-Smirnov scores. Non-significant results (Sig. value of >0.05) were considered to indicate normality. Histograms generated through this process were also considered for evidence of skewness or kurtosis. Of the variables examined, only pH passed this initial test, with a Kolmogorov-Smirnov score of 0.200, indicating normality. The dependent variable growth and three remaining independent variables, clay, coarse fragment, and EC, all failed to pass this assessment:  clay, coarse fragment, and EC (Table 6).

**Table 6.  Kolmogorov-Smirnov and Shapiro-Wilk tests of normality**

| | **Kolmogorov-Smirnov** | | | **Shapiro-Wilk** | | |
|---|---|---|---|---|---|---|
| | Statistic | df | Sig. | Statistic | df | Sig. |
| **Growth** | 0.134 | 171 | 0 | 0.936 | 171 | 0 |
| **Clay** | 0.097 | 171 | 0.001 | 967 | 171 | 0 |
| **Coarse fragment** | 0.79 | 171 | 0.011 | 0.942 | 171 | 0 |
| **pH** | 0.053 | 171 | 0.2 | 0.978 | 170 | 0.01 |
| **EC** | 0.237 | 171 | 0 | 0.639 | 171 | 0 |

I used IBM SPSS Statistics Data software® to generate an initial linear regression model for comparison purposes using cacti growth as the dependent variable and the soil characteristics as the independent variables which yielded the following results (Tables 5 to 8).

Mean growth for this data set was 3.5 cm, clay percentage averaged 13.6%, coarse fragment percentage averaged 47.7%, and mean pH was 6.9 (Table 7).  EC produced a mean value of 683.7 µS/cm with a large standard deviation of 697.2.

**Table 7. Descriptive statistics for non-transformed linear regression model.**

| | **Mean** | **Std. Deviation** | **N** |
|---|---|---|---|
| Growth (cm) | 3.471 | 4.53 | 171 |
| Clay (%) | 13.63 | 3.70 | 171 |
| Cfrag (%) | 47.70 | 9.02 | 171 |
| pH | 6.92 | .41 | 171 |
| EC (µS/cm) | 683.67 | 697.17 | 171 |

Table 8 provides the correlations between variables in this model. I expected to find that my independent variables showed some relationship to my dependent variable, preferably greater than 0.3. While clay and pH show the greatest levels of correlation at -0.179 and 0.140 respectively, both fall short of the 0.3 threshold. There is some correlation between each of the four soil variables and cactus growth, just not at the desired levels.

Table 9, the ‘Coefficients’ table, is useful in checking for problems with multicollinearity among our variables through examination of the two reported values, ‘Tolerance’ and VIF. Tolerance indicates how much variability of an independent variable is not explained by the other independents in the model; therefore, small values for Tolerance (less than 0.10) indicate multiple correlations with other variables. The values from this model range from 0.789 to 0.982. VIF is the inverse of the Tolerance value, so the relatively low values here (1.0180 – 1.2680) fall well below the higher end of the range (>10), supporting the absence of muticollinearity.

**Table 8. Variable correlations for non-transformed linear regression model.**

| | | **Growth** | **Clay** | **Coarsefrag** | **pH** | **EC** |
|---|---|---|---|---|---|---|
| Pearson Correlation | Growth | 1.000 | -.179 | -.092 | .140 | .062 |
| | Clay | -.179 | 1.000 | .033 | -.056 | .120 |
| | Cfrag | -.092 | .033 | 1.000 | -.020 | -.191 |
| | pH | .140 | -.056 | -.020 | 1.000 | -.401 |
| | EC | .062 | .120 | -.191 | -.401 | 1.000 |
| Sig. (1-tailed) | Growth | . | .010 | .116 | .034 | .210 |
| | Clay | .010 | . | .335 | .234 | .060 |
| | Cfrag | .116 | .335 | . | .399 | .006 |
| | pH | .034 | .234 | .399 | . | .000 |
| | EC | .210 | .060 | .006 | .000 | . |
| N | Growth | 171 | 171 | 171 | 171 | 171 |
| | Clay | 171 | 171 | 171 | 171 | 171 |
| | Cfrag | 171 | 171 | 171 | 171 | 171 |
| | pH | 171 | 171 | 171 | 171 | 171 |
| | EC | 171 | 171 | 171 | 171 | 171 |

**Table 9. Variable coefficients for non-transformed linear regression model**

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. | Correlations | | | Collinearity Statistics | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | | Zero-order | Partial | Part | Tolerance | VIF |
| 1 | (Constant) | -7.278 | 7.023 | | -1.036 | .302 | | | | | |
| | Clay | -.226 | .092 | -.184 | -2.444 | .016 | -.179 | -.186 | -.183 | .982 | 1.018 |
| | Coarsefrag | -.027 | .039 | -.054 | -.699 | .486 | -.092 | -.054 | -.052 | .950 | 1.053 |
| | pH | 2.085 | .910 | .188 | 2.292 | .023 | .140 | .175 | .171 | .829 | 1.206 |
| | EC | .001 | .001 | .149 | 1.775 | .078 | .062 | .136 | .133 | .789 | 1.268 |

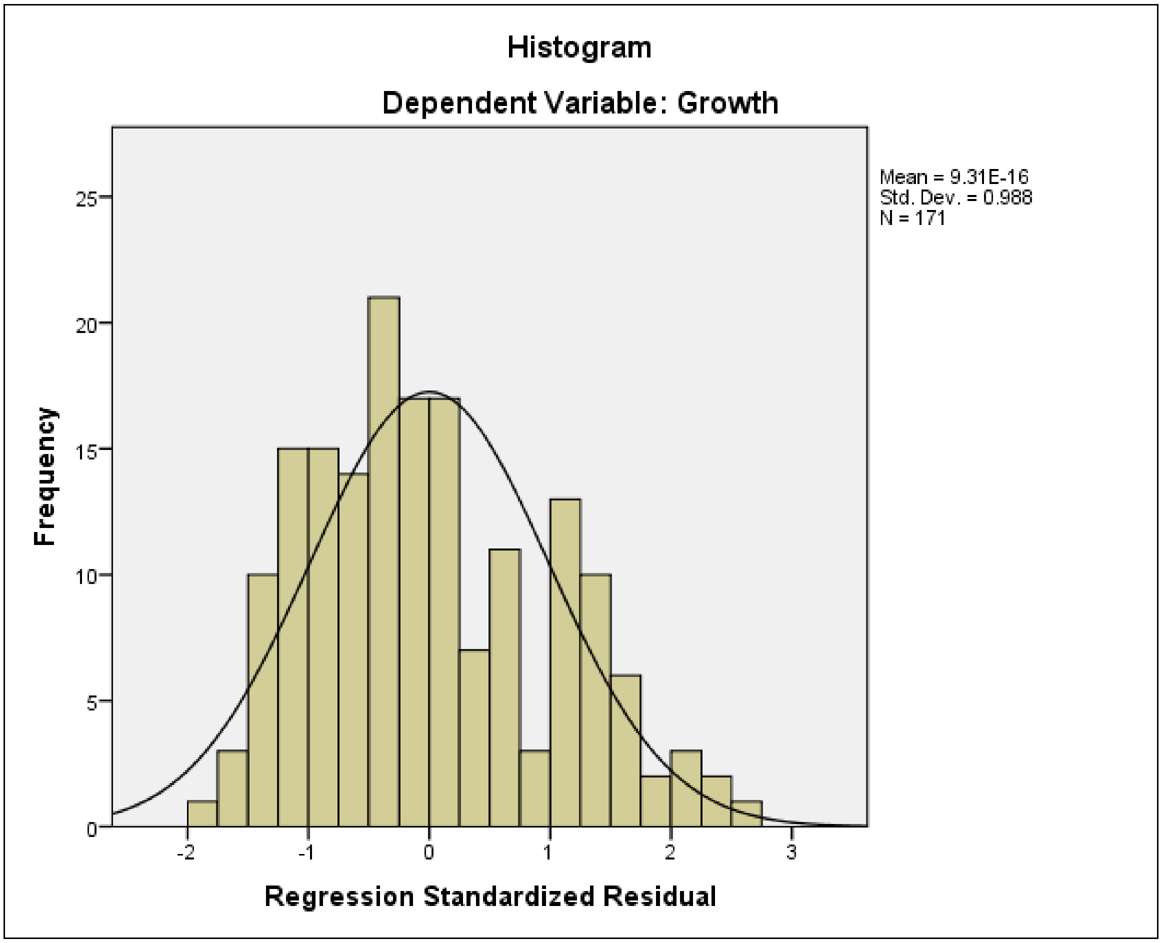
The independent variables can also be evaluated from Table 9. The ‘Beta’ values under ‘Standardized Coefficients’ allow the comparison of the contribution of each independent variable in the model. The largest beta coefficient, in this case -0.188, means that when the variance explained by all other model variables is controlled for, this variable, pH, makes the strongest unique contribution to explaining the dependent variable growth, followed closely by clay, then EC and finally Coarsefrag. However, to determine if these are statistically significant unique contributions, the ‘Sig.’ value must be checked. If any of these values are less than 0.05, the variable is significantly contributing uniquely to the prediction of the dependent variable growth. Ranging from .016 to 0.486, it would seem none of the variables make this contribution.

Table 10 allows the evaluation of the model. The R square value here tells how much of the variance in the dependent variable (growth) is explained by the model. Here, the R square value of 0.073 is rather low. This figure is interpreted as this particular model explains 7.3% of the variance in growth. With no significant contribution of any of the variables, and such a low R Square value, it would seem this model is not the best for predicting growth.

**Table 10. Model summary for non-transformed linear regression model.**

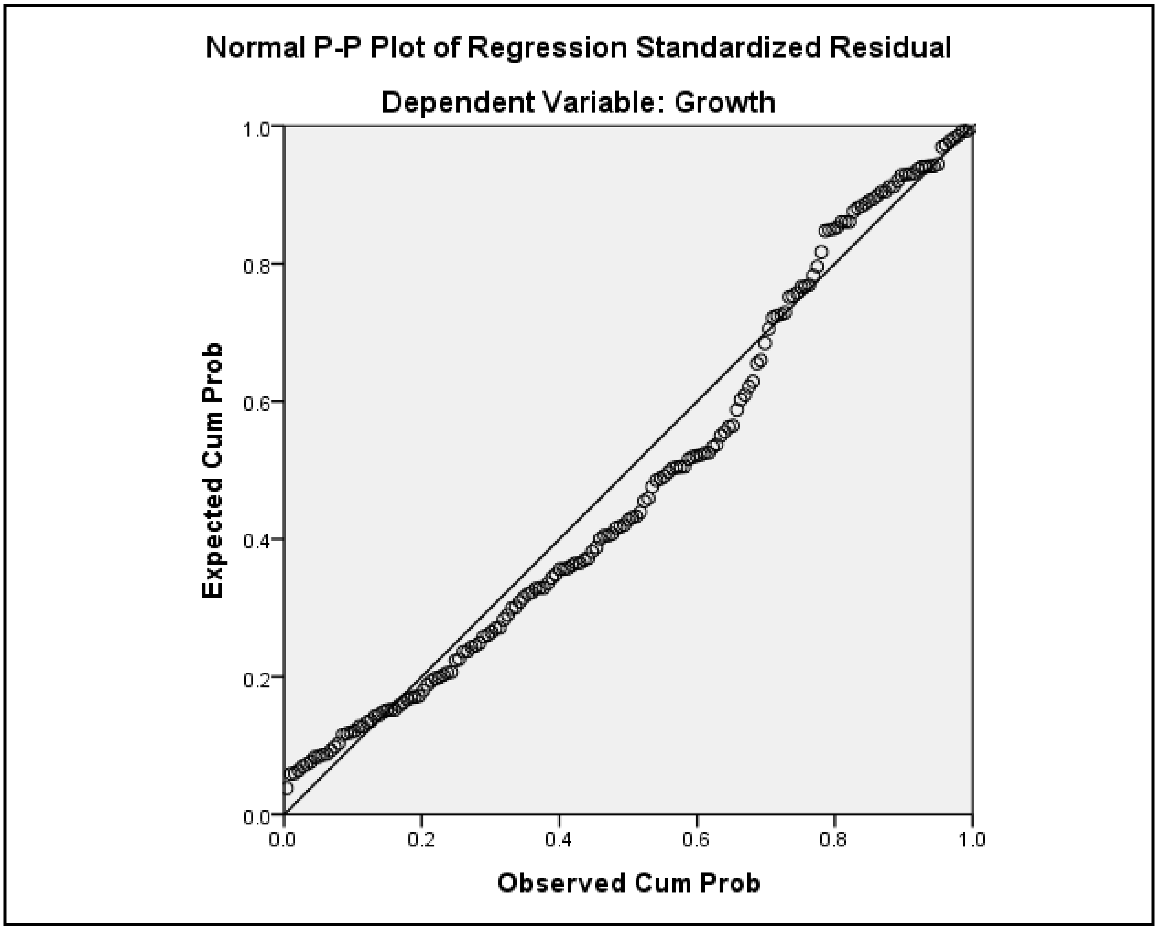
| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate | Change Statistics | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | R Square Change | F Change | df1 | df2 | Sig. F Change |
| 1 | .271 | .073 | .051 | 4.4202 | .073 | 3.283 | 4 | 166 | .013 |

**Figure 7. Histogram of non-transformed linear regression model**



The plotted histogram (Figure 7) and normal P-P plot of regression standardized residual (Figure 8) reflect the deviations from normality that the initial data investigation revealed.

**Figure 8. Normal P-P plot of regression standardized residual of non-transformed linear regression model.**



Thus, as the variables under consideration suggested considerable deviation from normality, I elected to ‘transform’ my variables in an attempt to modify the scores mathematically using various formulas until the distribution appeared more normal.

Based on the distribution histograms, I chose square root transformations for the ‘clay’ (SQRT(Clay)) and ‘growth’ (SQRT(Growth)) variables, a logarithmic (LG10(EC)) transformation for ‘EC’, and a reflect and logarithmic transformation (LG10(K-Coarsefrag)) for the ‘coarse fragment’ variable, where ‘K’ = the largest possible value +1 (71.2).

**Table 11. Descriptive statistics for transformed linear model**.

| | **Mean** | **Std. Deviation** | **N** |
|---|---|---|---|
| SQRT(Growth) | 2.03 | 1.01 | 128 |
| pH | 6.92 | 0.41 | 171 |
| SQRT(Clay) | 3.66 | 0.50 | 171 |
| LG10(EC) | 2.71 | 0.31 | 171 |
| ReflectLog10(CFrag) | 1.33 | 0.20 | 171 |

Descriptive statistics for the transformed variables are given in Table 11. The square root of growth had a mean of 2.03, down from the pre-transformed average of 3.47, average pH remained at 6.92, the square root of clay average dropped to 3.66 from 13.63, log of electrical conductivity averaged 2.71, and the transformed coarse fragments had a mean value of 1.33.

**Table 12. Variable correlations for transformed linear regression model.**

| | | **(Growth)** | **pH** | **(Clay)** | **(EC)** | **(CFrag)** |
|---|---|---|---|---|---|---|
| Pearson Correlation | (Growth) | 1.000 | .238 | -.276 | -.023 | .150 |
| | pH | .238 | 1.000 | -.048 | -.322 | .123 |
| | (Clay) | -.276 | -.048 | 1.000 | .161 | -.084 |
| | (EC) | -.023 | -.322 | .161 | 1.000 | .120 |
| | (CFrag) | .150 | .123 | -.084 | .120 | 1.000 |
| Sig. (1-tailed) | (Growth) | . | .003 | .001 | .398 | .046 |
| | pH | .003 | . | .266 | .000 | .055 |
| | (Clay) | .001 | .266 | . | .018 | .136 |
| | (EC) | .398 | .000 | .018 | . | .059 |
| | (CFrag) | .046 | .055 | .136 | .059 | . |
| N | (Growth) | 128 | 128 | 128 | 128 | 128 |
| | pH | 128 | 171 | 171 | 171 | 171 |
| | (Clay) | 128 | 171 | 171 | 171 | 171 |
| | (EC) | 128 | 171 | 171 | 171 | 171 |
| | (CFrag) | 128 | 171 | 171 | 171 | 171 |

(Variable) designates transformed variables

Correlation values (Table 12) rose for the transformed model for the pH, clay and coarse fragment variables, but dropped for EC, from 0.062 to a negative correlation of -0.023. The square root of clay has the greatest correlation at -0.276, pH follows at 0.238, and the transformed coarse fragment variable at 0.150. The logarithmic transformation of EC correlated at the lowest level, -0.023. None of the variables correlated at our desired threshold above 0.3.

Tolerance and VIF numbers in our coefficients table (Table 13) again reflect the absence of multicollinearity, with all tolerance values well above the 0.10 level and VIF values ranging from 1.039 to 1.183, none of which approach the higher end of the range at ten or greater. Beta values in Table 11 show the square root of clay variable having the greatest unique contribution to explaining growth at -0.271, pH with a positive influence at 0.242, and relatively low contributions from the transformed EC (0.088) and coarse fragment (0.086) variables. The soil pH and the transformed clay variables make significant contributions at 0.008 (pH) and 0.002 (clay), both well below the desired threshold of less than 0.05. Neither the transformed EC (0.332) nor coarse fragment percentages (0.316) variables meet the preferred significance level of less than 0.05.

**Table 13. Variable coefficients for transformed linear regression model**

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. | Correlations | | | Collinearity Statistics | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | | Zero-order | Partial | Part | Tolerance | VIF |
| 1 | (Constant) | -1.467 | 1.988 | | -.738 | .462 | | | | | |
| | pH | .599 | .221 | .242 | 2.708 | .008 | .238 | .237 | .226 | .869 | 1.150 |
| | SQRT(Clay) | -.551 | .173 | -.271 | -3.185 | .002 | -.276 | -.276 | .266 | .963 | 1.039 |
| | LG10(EC) | .288 | .296 | .088 | .973 | .332 | -.023 | .087 | .081 | .845 | 1.183 |
| | ReflectLog10CFrag | .438 | .435 | .086 | 1.007 | .316 | .150 | .090 | .084 | .945 | 1.058 |

**Table 14. Model summary for transformed linear regression model.**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate | Change Statistics | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | R Square Change | F Change | df1 | df2 | Sig. F Change |
| 1 | .378 | .143 | .115 | .95070 | .143 | 5.138 | 4 | 123 | .001 |

The transformed variables do a better job in explaining how much of the variance in growth is explained by the model with an R square value of 0.143 (Table 14), up from 0.073 prior to the transformation (Table 10). We can interpret this to mean that 14.3% of the variance in saguaro transplant growth is explained by this model, with significant contributions from the pH variable and the square root transformation of the clay variable.

The Histogram of transformed linear regression model (Figure 9) shows the actual shape of the distribution for the model. Despite a rather large deviation at the -0.1 level, the overall distribution resembles a normal distribution shape once the transformation has been applied, with no skewness or kurtosis. In the Normal P-P Plot (Figure 10) I hoped that the data points would lie in a reasonably straight diagonal line from bottom left to top right, suggesting no major deviations from normality, and this is clearly shown in that figure.

**Figure 9. Histogram of transformed linear regression model**

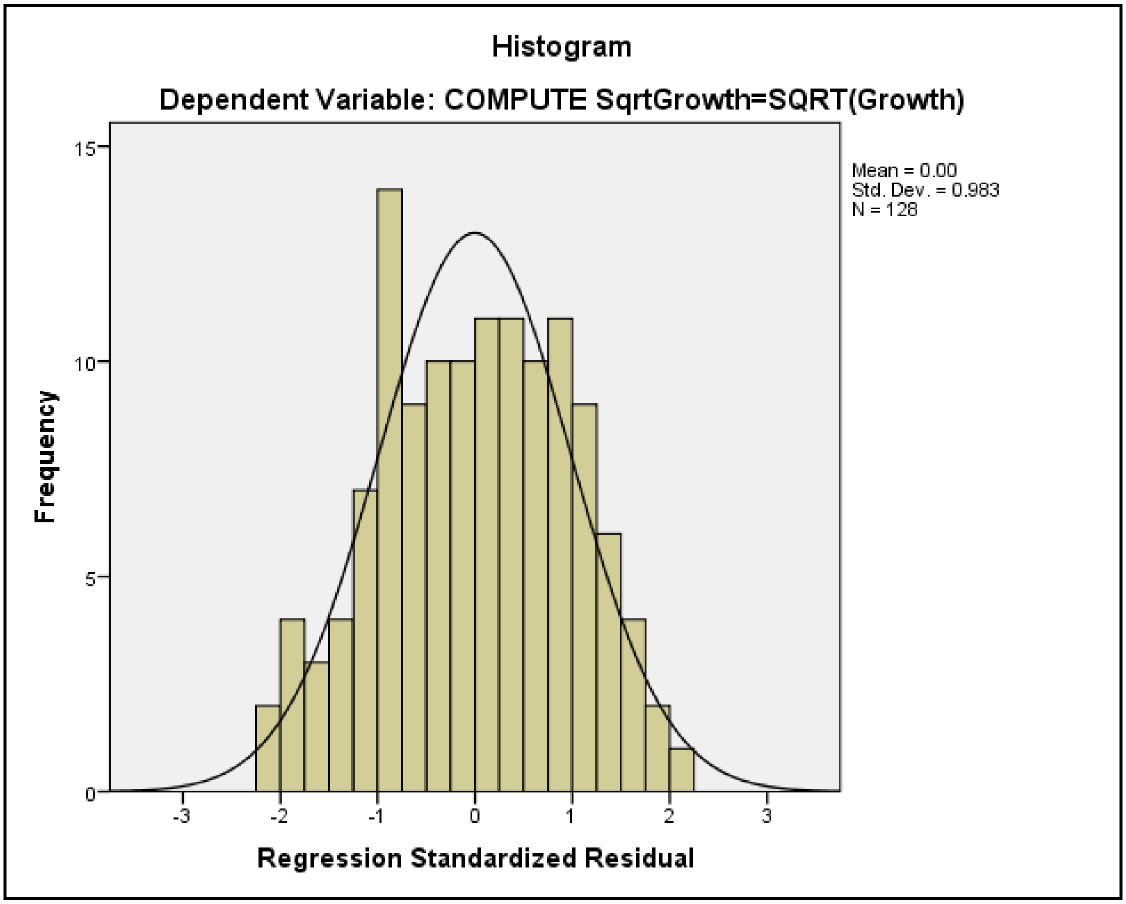
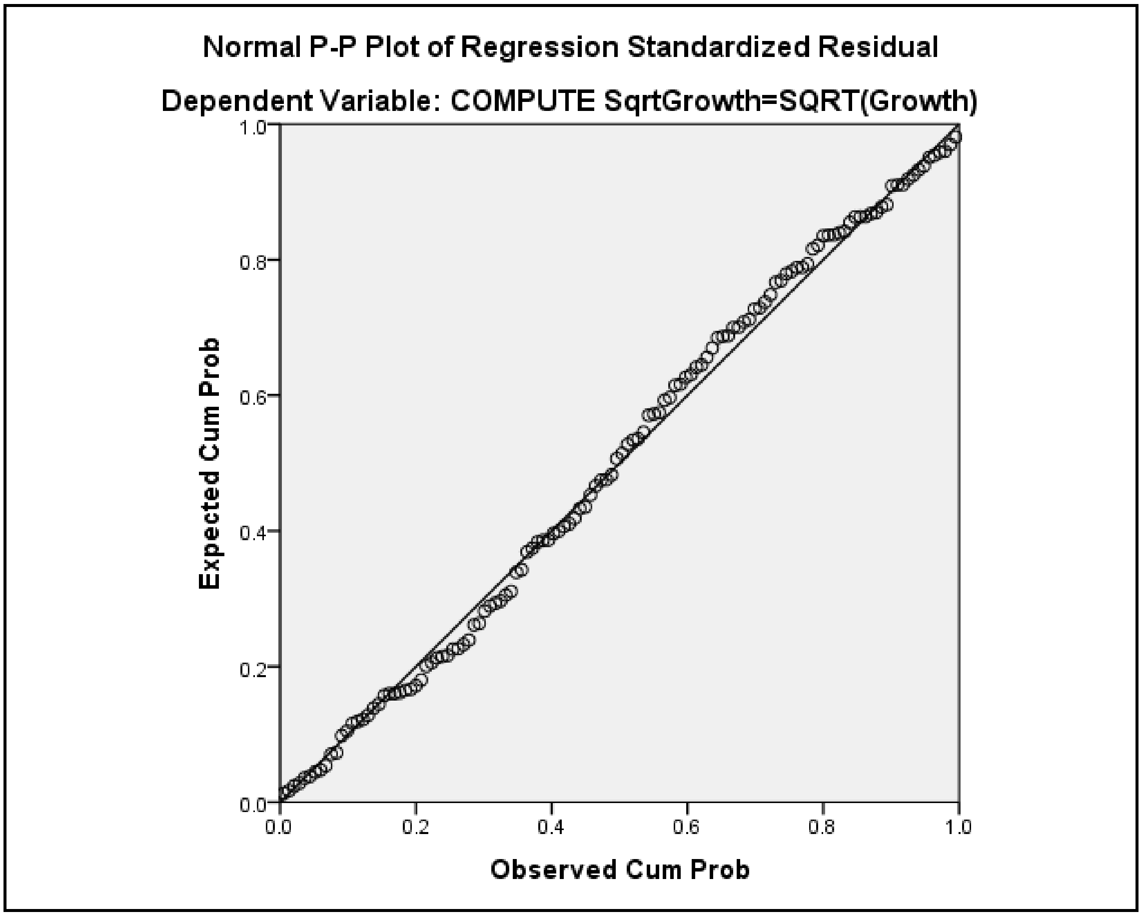


**Figure 10. Normal P-P plot of regression standardized residual of transformed linear regression model.**



# Chapter 6

# DISCUSSION AND CONCLUSIONS

There have been few large scale saguaro transplant projects to date, and even less focus on saguaro transplanting in post wild fire areas. The magnitude of the influence of saguaro on surrounding wildlife has been well documented (Fleming, and Valiente-Banuet, 2002; Wolf and Rio, 2003; Goad and Mannan, 1987; Hardy and Morrison, 2000; Gilman, 1915; Stutchbury, 1991; Wolf, Martíbez, and Babson, 2002); the critical role the saguaro plays in the Sonoran desert ecosystem justifies focus on re-establishment of saguaro stands decimated by wild fire. While there are many variables that influence saguaro establishment and success, such as altitude, topography, nurse plant associations, soil moisture content and retention, and precipitation, selection of optimal transplant sites is a complex process. Local soil variables such as coarse fragment percentages, texture, pH, and electrical conductivity are attractive predictive considerations as collection of soil samples is uncomplicated and laboratory analysis of these variables is comparatively inexpensive and expedient.

Saguaros have been observed to establish in higher numbers in coarser, rockier soils (Steenbergh and Lowe, 1969). It is reasonable to assume that the transplants in our study would also exhibit higher growth rates and survivorship in the transplant sites with greater percentages of coarse fragments, although in this study that correlation was not observed. As soil texture influences soil water depletion, water potential, plant water stress (Deb, Shukla, Sharma, and Mexal, 2013) and field water capacity (Jabro et al, 2009), and has been observed to influence saguaro distributions (Parker, 1988), I expected to find significant correlation between soil texture values and growth, however, the analyses did not support this hypothesis.

Multiple regression analysis was used to assess the ability of four soil variables to predict saguaro transplant growth. Preliminary analyses were conducted to confirm no violation of the assumptions of normality, multicollinearity and homoscedasticity. Kolmogorov-Smirnov scores indicated deviations from normality for the soil variables EC, clay, and coarse fragment percentages, as well as the dependent variable, growth. The data were transformed mathematically: square root transformations for the clay and growth; logarithmic transformation for electrical conductivity, and reflect and logarithmic transformation for the coarse fragment variable. Post transformation regression modeling revealed pH and clay as making significant contributions to explaining the dependent variable growth, with standardized Beta coefficients of 0.242 (pH) and -0.271 (clay) with significance values of 0.008 and 0.002, respectively. The total variance explained by the model as a whole was 14.3%, $F$ (4,123) = 5.14, $p < .005$.

With the rather low R square value and percentage of the variation in saguaro growth explained by the transformed linear regression model, it may prove useful for land managers to consider factors other than soil variables in site selection for saguaro transplant efforts.

During the field data collection, observed desiccation and eventual mortality among the transplants suggested patterns influenced by topography, specifically slope and aspect. As topography can result in variation in soil water retention, precipitation runoff and erosion of topsoil, a consideration of these variables with regard to transplant success might prove more useful.  Desiccation caused the highest numbers of cacti mortality, followed by predation.  Closer examination of these cacti and their specific slope and aspect values might reveal patterns in the topography that influence soil water retention and cacti survival.

The transplant mortality I witnessed during the field data collection phase was largely due to desiccation, 42 of the 200 transplanted cacti (Table 1).  Desiccation mortality was entirely among the smaller size cacti (about 5 to 6 cm), while the larger class of transplants (20 to 60 cm) suffered no mortality during the measurement phase either from desiccation or predation.  The smaller cacti would appear to be unable to store sufficient water resources to resist the most extreme episodes of high temperature and low precipitation. However, at a certain point the plant also becomes too heavy for transport and suffers damage during the uprooting and shipping process when it requires supine positioning for transport (personal communication, Richard Lahti, Arizona Riches Cactus and Succulents).  This creates an optimal size for transplants between the lower end of the range which is limited by water retention capacity and possible desiccation, and a higher limit due to transplant injury during transport.  Impending restoration efforts should consider selection of transplant saguaro in an older age class with a height range from about 15 cm to an upper limit of about 25 cm.

As the initial planting events occurred in late March and early April, the cacti were almost immediately subjected to the hottest and driest time period of the year between cooler spring temperatures and the seasonal monsoon rains of late June through July and August that are so critical to Sonoran vegetation and wildlife.  This undoubtedly played into the high mortality rates observed within the smaller sized cacti. Future transplant efforts could consider planting dates in the mid to late months of the fall, providing more moderate temperatures for establishment and allowing the cacti to benefit from the seasonal winter rains that the Sonoran desert undergoes annually.

While the cacti were systematically located in proximity to *A. greggi* nurse plants, there was considerable observable variation in the canopy cover densities within the nurse plants selected (Figure 11). Canopy cover density can influence shade, soil and ambient air temperatures, soil moisture, and photosynthetically active radiation (PAR) levels, all factors in saguaro seedling establishment and vigor. Turner (1966) observed one hundred percent mortality among unshaded saguaro seedlings within one year. A closer focus on canopy cover density and measured PAR levels may yield a superior estimate of favored selection sites for transplant efforts.

Turner (1966) found that saguaro seedling mortality differed among soils of varying albedo. Seedling mortality was lower in soils with higher albedo and greater in soils that were darker and hotter. I observed considerable variation in soil color during the collection process and texture analysis (Figure 12). There is a possibility that the variation in soil color could have influenced survivorship and growth, and could merit consideration in transplant site selection.

As wild land fires adversely affect Sonoran desert plant communities with few evolved fire adaptations, and wild fires would appear to be a recurring event under current environmental conditions in the Sonoran Desert, land managers would do well to further explore the feasibility of large scale, post-wild fire restoration projects. With the recognition of the great influence the saguaro has on its surroundings by providing essential nutrients, water, nesting sites, and microclimate, re-establishment of saguaro communities could prove to be one of the most useful distributions of management resources toward ecological restoration of damaged post fire Sonoran desert ecosystems.

This study set out to establish the potential relationships between saguaro transplant growth and the readily obtainable soil characteristics of texture, coarse fragments, pH, and electrical conductivity. However, while some significant correlation was established between saguaro transplant growth and the soil pH and clay content variables, the application of these soil characteristics as predictors of optimal planting sites might not in reality prove useful. Selection of future restoration sites for saguaro could concentrate on topography, particularly slope and aspect, nurse plant canopy densities, nurse plant species, elevation, soil albedo, or climate modeling. Sonoran desert post fire ecosystem recovery is a complex process, and the identification of supplementary features in restoration site selection that could assist in potential project success is a useful allocation of management resources.

**Figure 11. Variation in canopy density of *A. greggii*. Tonto National Forest, U.S.A. June 2007.**

Figure 12.  Observable variation in soil color during texture analysis.

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