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Physical and chemical soil properties affecting the growth habits of agave species

Hara, Yuto, M.S.

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U·M·I
300 N. Zeeb Rd.
Ann Arbor, MI 48106

PHYSICAL AND CHEMICAL SOIL PROPERTIES AFFECTING THE GROWTH HABITS OF AGAVE SPECIES

by

Yuto Hara

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APPROVAL BY THESIS DIRECTORS

This thesis has been approved on the date shown below:

Donald F. Post — 7/20/92

Dr. Donald F. Post
Professor of Soil and Water Science
Date

Robert G. McDaniel — 7/27/92

Dr. Robert G. McDaniel
Professor of Plant Sciences
Date

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ABSTRACT

Nine physically and chemically different soil samples from five study sites in which agaves grew, or were grown, were investigated to evaluate the effects of soil physical and chemical properties on the growth habits of agaves. In five Arizona study sites, biomass data of seven agave species has been recorded for the past ten years. Agaves were grown experimentally in the greenhouse using two widely different soil types from the five sites to evaluate growth under controlled conditions. Influence of edaphic factors on agave growth for the study sites and greenhouse experiment was evaluated. The results shows that the determinant primary factors were water availability and temperature. Soil texture, soil pH, soil CO_2 concentration, nitrogen, and soluble salt concentration were placed as influential secondary factors for the growth of agave. The degree of influence of these soil factors depends highly upon the genetic characteristics of agave species.

1. INTRODUCTION

Arid lands have low precipitation and high temperature by nature, and these climatic characteristics bring about sparse vegetation and low soil fertility. To compensate for the climatic disadvantages, the input of a massive amount of irrigation water and fertilizer is indispensable in the farming of arid lands. This intensive irrigated agriculture requires more energy input than that of more humid regions; however, this will need some modification or total change to prepare for the coming fossil fuel and water shortage era.

One alternative agricultural technology for southern Arizona will be the use of arid land plants. Desert plants genetically have drought tolerance and physiologically and morphologically have mechanisms to avoid water deficiency. The major problem is that plant productivity of arid lands is low compared with that of humid lands. Fischer and Turner (1978) reported that the annual plant productivity in the arid zones ranges from 25 to 400 g m^{-2}, while the productivity in humid zones is up to 3000 g m^{-2}.

There are, however, desert plants which exhibit high productivity with minimal supplementary energy input. One such plant is agave, which is a perennial desert plant. Several species of agave have been grown mainly as a fiber crop. There are about 140 species in the agave family and there are several other usages for agave besides fiber (Gentry, 1982). The introduction of agave culture not only makes low input farming possible but could also alleviate problems in Arizona agriculture such as the increasing cost of water and decline of water table and ground water contamination caused in the past by irrigated agriculture.

There is limited research which approaches agave in terms of agronomic interest. Especially, the relationships between soil properties and agave growth have not been studied in detail in spite of the presence of successful long term agave culture in the arid and semiarid regions of several countries. To establish an effective production system of agave in arid zones, the responses of agave to various levels of physical and chemical soil properties must be investigated.

My research objectives are: 1) to evaluate the effects of soil physical and chemical characteristics on the growth of agave species, 2) to estimate the extent of climatological influence in agave growth, 3) to investigate the interaction of soil properties and climatological factors on agave, 4) to determine optimum soil conditions for agave culture in arid zones, and 5) to discuss the feasibility of agave as an alternative crop in Arizona.

2. LITERATURE REVIEW

History of Agave

The origin of agaves is considered to be the highlands in Mexico, where people have used agaves as materials for food and fiber for at least 9,000 years (Callen, 1965). Native Americans and Mexicans of the Sonoran Desert are thought to have utilized *Agave murpheyi*, which was one of the ancient Indian cultivars in southern Arizona, for a sweet and nutritious food called mescal (Crosswhite, 1981). They had their own agricultural system for agave cultivation called rockpile fields which were composed of disintegrated cobbles and pebbles on valley slopes or bajadas (Fish et al., 1985). There are two major causes for the decline of agave culture: one is the decrease of native people population caused by the spread of Old World diseases, and the other is the introduction of Old World cultivars rich in sugar, such as melons, peaches, apricots, quinces, pears, apples, and sugar cane (Dobyns, 1988). Today, agaves are mainly grown for fiber production in the arid and semiarid regions of several countries (Brucher, 1989). Mexico has the highest agave production in the world, and many species of agave have been used for an alcoholic beverage and fiber production (Gentry, 1982). Present agave culture in Mexico highly depends on empirical cultivation methods. This is due to the natural logic that the most favorable environmental conditions for the growth of a plant are provided in the place of a plant's origin. Generally, agave culture throughout the world has been carried out in regions with warm climates and sandy soils.

Botanical Aspects of Agave

Agaves are perennial plants found in arid and semiarid regions of north and central America, and Figure 1 shows the typical morphological features of agave. The succulent green leaves form a rossete by spirally radiating horizontally from the ground to upright without exposing a trunk. A terminal spine of each leaf is long and sharp, and short spines and teeth exist along the margins of leaves. These morphological features of agave are beneficial for survival of plants in dry zones. Succulent agave leaves act as water reservoirs and the sharp spines are effective in preventing attack by herbivores in the sparse vegetation of dry environments. Trough-like leaves and the radial pattern

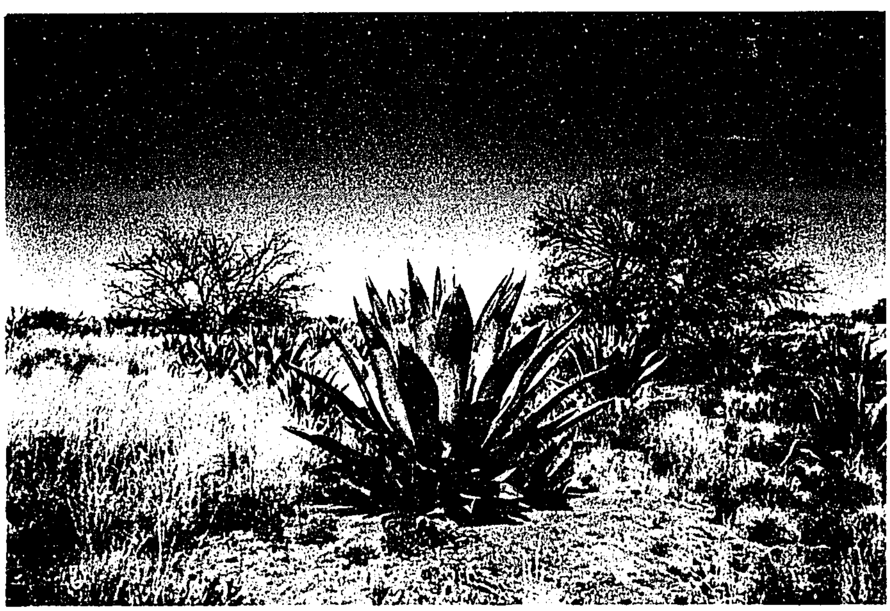

Fig. 1. The agave (*Agave americana*) plant.

of those leaves are suitable for collecting raindrops and effectively leading running water to the base of the stem (Brucher, 1989; Gentry, 1982).

The carbon metabolism of agave also helps this plant adapt to arid and semiarid environments. Agave is one of the plants which exhibit Crassulacean Acid Metabolism (CAM). Kluge and Ting (1978) described the characteristics of CAM metabolism: 1) malic acid accumulates during the night period and is metabolized during the day time, 2) the fluctuation of carbohydrates in the photosynthetic tissues occurs inversely with the fluctuation of malic acid, and 3) most of the CO_2 fixation from the atmosphere occurs during the night. As a result, transpiration from stomates during the day time is closely controlled. Agave stores carbohydrates for a few decades for one season's flowering and then dies (Crawford, 1989). Agave adapts well morphologically and physiologically to arid and semiarid environments.

Agave as an Alternative Crop in Arizona

McDaniel (1985) proposed the utilization of native arid land plants such as agave to produce acceptable profit and minimize agricultural inputs such as irrigation water, fertilizer application and maintenance in the agriculture of southern Arizona. He recommends multipurpose uses of agave: for instance, fiber production, production of steroidal sapogenins, production of ethanol, animal fodder, soil erosion control, promotion of range grass reestablishment, and ornamental use.

Reports concerning a possible energy shortage in the near future give considerable persuasive power to McDaniel's proposal, which offers an alternative agricultural option for southern Arizona. Oil and natural gas are indispensable natural resources for the present irrigated intensive agriculture to drive agricultural machinery and manufacture nitrogen fertilizers, but these natural resources are not infinite. Hirsch (1987) and Kerr (1989) predicted that these resources will be consumed in the early twenty-first century. Pimental and Dazhong (1990) calculated calorie consumption of agriculture per hectare and reported the transition of energy consumption in each agricultural procedure from 1700 to 1983. The energy consumption by irrigation and fertilizer in U.S. agriculture account for 12% of the total consumption in 1945, 30% in 1964, 49% in 1975 and 58% in 1983.

The intensity of energy use is greater in the agriculture of arid lands than other regions, because arid regions have extremely low precipitation and naturally low soil fertility, which requires additional resources. Average annual precipitation is less than 250 mm in the southwestern part of Arizona and 500 mm in the lower elevations of the eastern part, and most Arizona soils average less than 1 percent organic matter due to low productivity of natural vegetation and rapid decomposition of dead plants (Hendricks, 1985). Therefore, agriculture in Arizona must rely upon a massive amount of irrigation water and fertilizers to keep productivity high. For these reasons, Arizona needs to evaluate alternative agriculture which minimizes agricultural inputs and improves the energy efficiency per unit agricultural product.

Relationships Between Climatological Factors and Agave Growth

Climate plays an important role in the determination of the characteristics of the plant community and soil in nature. There are many parameters which characterize climate: for example, hours of sunlight, temperature, precipitation, humidity, evapotranspiration, wind, and others. Temperature and precipitation are the primary influential factors in the development of the plant community and the formation of soil (Hendricks, 1985; Allen, 1991).

According to Kearney and Peebles (1960) and Gentry (1982), 12 species of agave are native to Arizona. Those agaves are listed in Table 1 with their distribution in Arizona and the ranges of altitude, precipitation, and temperature within which each agave species occurs. Agaves are distributed in almost all of Arizona except for the northeastern regions. Their natural habitats are at elevations between 152 and 2438 m. Most agaves require about 500 mm of average annual precipitation for their growth. *Agave deserti* and *A. murpheyi* can grow in a desert environment whose precipitation is less than 250 mm, which indicates that these two species have drought resistance. Most species do not occur or grow vigorously in the places where the mean air temperature is below the freezing point in January and reaches up to 32 °C in July. *A. kaibabensis* and *A. utahensis*, however, can survive below 0 °C in January, but generally speaking, agaves are plants which adapt to warm environments. However, from the ecological point of view, each species has its own favorable climatic conditions for growth.

Table 1. List of agaves found in Arizona[a].

Species	Altitude (m)	Average annual precipitation (mm)	Mean air temperature (°C) Jan.	Jul.	Distribution (County)
Agave americana[b]	1210-1820	250-375	4-7	24-27	Cochise, Pima (grown as an ornamental)
A. arizonica[c]	914-1372	250-500	7-13	27-32	New River Mountains of Yavapai and Maricopa
A. chrysantha	914-2134	375-500	4-10	24-29	Gila, eastern Maricopa, Pinal, Pima
A. deserti	152-1067	130-250	7-13	29-32	Northern Coconino, western Yavapai, southern Mohave, southwestern Pima, northern Yuma
A. kaibabensis	2425	375-635 or >635	-4--1	16-21	Kaibab Plateau of Coconino
A. mckelveyana[c]	914-1829	250-500	2-7	21-27	Mohave, Yavapai
A. murpheyi	460-930	130-500	4-10	27-32	Paradise Valley of Maricopa, Roosevelt and Tonto Basin of Gila, Queen Creek of Pinal
A. palmeri	1067-2286	250-500	4-10	24-29	Graham, Cochise Gila, Santa Cruz, Pima
A. parryi	1372-2438	375-635	2-7	21-27	Southern Coconino, Yavapai, Cochise, Santa Cruz, Pima
A. parviflora	1372	375-500	4-7	21-27	Mountainous region of Santa Cruz
A. schottii	1219-2134	250-500	4-10	24-29	Gila, Pinal, Cochise, Santa Cruz, Pima
A. toumeyana	610-1524	375-635	4-10	24-29	Mountainous region of Gila and Pinal, Fish Creek Hill of eastern Maricopa
A. utahensis	914-2286	130-375	-1-4	21-27	Coconino, Mohave

Table 1. List of agaves found in Arizona[a], continued

[a]. All data of precipitation and temperature were referred to Hendricks (1985). Species of agaves, altitude, and distribution were cited from Kearney and Peebles(1960) and Gentry (1982).

[b]. This species is not native to Arizona (Gentry, 1982; McDaniel, personal communicatiom, 1992).

[c]. These species were cited from Gentry (1982).

The elevation and topography of land affect precipitation, temperature, and solar radiation. In general, the amount of precipitation increases and atmospheric temperature decreases as elevation goes up, and slope aspect and gradient influence the supply of solar radiation receieved by plants. Nobel and Hartsock (1986a) examined the productivity of *A. deserti* at various elevations in the northwestern Sonoran Desert. Their results showed that nighttime temperatures were suitable for the growth of the species at higher elevations in the summer and at low elevations in the winter. They also reported that the aspect and steepness of slope influenced the length of time agaves received solar radiation. The number of unfolded leaves during the winter was 7.3 per 10 plants for south-facing steep slopes, but 0.7 for north-facing steep slopes. Elevation and topography are the factors which influence precipitation, temperature, and hours of sunlight, which in turn directly affect the formation of a plant community in an area. Elevation and topography are primary variables to characterize the plant community of an area; but they are not used as the environmental parameters to examine plant growth in the field.

Table 1 provides the approximate moisture level which agaves require for growth. From Table 1, most agaves grow well under the environments whose average annual precipitation is about 500 mm. This amount of precipitation cannot support other conventional crops; for example, rice, wheat, corn, and barley. Precipitation greater than 635 mm is excessive moisture for agaves.

Agaves effectively utilize the limited water supplied by occasional precipitation to survive in arid and semiarid regions. Water use efficiency (WUE) is one of parameters which indicates the productivity of plant. WUE is generally defined as the ratio of the benefit gained to the water used (Singer and Munns, 1987). CAM plants exhibit much higher WUE than those of C_3 and C_4 plants (Osmond, 1978; Kluge and Ting, 1978; Nobel, 1983a; Winter, 1985). The average WUE values are 1 to 3 for C_3 plants , 2 to 5 for C_4 plants, and 10 to 40 mg CO_2 g H_2O^{-1} day^{-1} for CAM plants (Nobel, 1983a). The WUE values of *A. americana* and *A. deserti* are 20 (Neales et al., 1968) and 40 mg CO_2 g H_2O^{-1} day^{-1} (Nobel, 1976), respectively.

Agaves usually occur in warm climates as Table 1 shows. However, the range of high and low temperature tolerances of agaves varies among species. Nobel and Smith (1983) examined high and low temperature tolerances of 14 species of agave. Species from cool habitats such as *A. utahensis* and *A. parryi* exhibited greater low temperature tolerances than species grown in warm regions: an average temperature tolerance of *A. utahensis* and *A. parryi* was -19 °C, but on the other hand that of *A. americana* was -7 °C. All species examined showed great high temperature tolerances which ranges from 57 °C to 65 °C. Nobel and McDaniel (1988) reported more low temperature sensitive species than *A. americana*. At the Marana Agricultural Center, Tucson, Arizona, where mean minimum air temperature in January was 4 °C, 53% of the expanded leaves for *A. sisalana* were killed and 35% of expanded leaves of *A. vilmoriniana* exhibited evidence of cold injury during winter, but *A. americana* experienced less cold damage than the other two at the Oracle Agricultural Center (Page Ranch), Tucson, Arizona, where is the colder place: 20% of unfolded leaves showed necrosis.

Relationships Between Soil Properties and Agave Growth

Soil Texture Affecting the Behavior of Soil and Plant

Below soil surfaces, plants utilize moisture, oxygen, and nutrients in the soil through root systems, and the optimum levels of moisture, oxygen, and nutrients required depend upon the biological characteristics of the plant. Physical and chemical soil properties affect the amount and movement of these essential substances for plant growth and the development of root systems. In the Sonoran desert of North America, species of plant communities correlate with particle size distribution and soil salinity (Phillips and MacMahon, 1978). Plants have their own favorable physical and chemical soil conditions.

Physical and chemical soil properties are largely influenced by soil texture (Hillel, 1982). Soil texture represents the relative proportions of three separable particle size ranges called sand, silt, and clay in the soil (Hillel, 1982). The diameter ranges of the three particles separates are; sand - 2 to 0.5 mm, silt - 0.5 to 0.002 mm, and clay - less than 0.002 mm (USDA classification cited in Hillel, 1982). The fractions larger than 2 mm in diameter are referred to as coarse fragments (Singer and Munns, 1987).

The first concern in the relationship between soil texture and plant growth will be the behavior of roots in different textured soils. Soil texture, however, influences root growth in an indirect manner through the direct response of roots to changes of soil water availability, soil aeration, and nutrient contents, which are directly affected by soil texture (Glinski and Lipiec, 1990).

Water availability is the most limiting factor for plant growth in arid and semiarid regions (Fischer and Turner, 1978). Water supply for plants or water availability to plants in arid regions highly depends upon soil texture, which controls hydraulic conductivity and field capacity (Walter and Stadelman, 1974). Since rain water penetration in coarse textured soils is much deeper than that in fine textured soils, evaporation from coarse textured soils is much less than that from fine textured soils after rainfall (Walter and Stadelman, 1974). Consequently, soils containing lots of cleft rocks are the best water supplier to desert plants (Hillel and Tadmor, 1962; Walter and Stadelman, 1974). This may help explain why agaves frequently occur in coarse textured soils containing rock fragments (Gentry, 1982).

The clay content of soil, types of clay minerals, and organic matter content are important factors for estimation of soil fertility because only clay particles and soil organic matter can hold or exchange cations, and organic matter is also an important nitrogen source in nature. Habitats of agaves are usually sandy soils low in clay and organic matter, so the growth rate of agaves is generally low in nature.

Soil Aeration and Agave Growth

Desert succulents have shallow and coarse root systems and occur in well-aerated soils such as sandy soils (Cannon, 1911). Most cacti develop their roots in the upper 3 - 15 cm of the soil (Cannon, 1911; Nobel, 1977a), and roots of *Agave deserti* occur about 15 cm below the soil surface (Nobel, 1976). Agaves tend to occur in highly aerated soils such as sandy soils rather than clayey soils (Nobel, 1988). Table 2 also indicates that all agaves in Arizona prefer well-aerated conditions in their natural habitats, which are rocky and stony mountain slopes whose soils contain high percentage of coarse fragments and sand. Since sandy textured soils have a large number of macro pores in comparison to clayey soils, air diffuses through sandy soils more rapidly than clayey soils (Singer and Munns, 1987).

Palta and Nobel (1989) suggested that the CO_2 concentration in the soil might be a key factor explaining why roots of desert succulents occur in the upper layer of sandy soils. They examined the root respiration rate of *A. deserti* at various levels of soil CO_2. Consequently, the respiration rate for roots of *A. deserti* was drastically reduced at the 1% level of CO_2 in soil which is the typical CO_2 level in the root zone of various plant species in clay loam and silt loam. Root cells of *A. deserti* were killed in about 4 hours in a soil atmosphere of 2% CO_2.

Table 2. Natural habitats of agaves in Arizona[a].

Species	Habitats
Agave americana	Broad tolerance to different soil types
A. arizonica	Chaparral and juniper grassland community over volcanic pediments
A. chrysantha	Granitic and volcanic mountain slopes, chaparral and juniper communities, and pine woods
A. deserti	Desert (sandy soils)
A. kaibabensis	Prefer limestone and broad open stony slopes
A. mckelveyana	Chaparral and juniper associations on rocky slopes
A. murpheyi	Mountain slopes of low elevation
A. palmeri	Limestone and granite slopes, rocky brush slopes in low elevation
A. parryi	Rocky slopes of the grama grassland, the oak woodland, the pine and oak forests, and chaparral
A. parviflora	Mountain rocky slopes
A. schottii	Rocky slopes with grama grasslands and oak woodland biomes
A. toumeyana	Limestone and volcanic rocks with highland desert vegetation to the chaparral and lower pines; on open rocky ledges
A. utahesis	Limestone and open stony slopes

[a]. Description of habitats of agaves were referenced to Gentry (1982).

Nobel (1990a) reported that the limiting factor of desert succulents response to well-aerated soils is not the amount of O_2 but the soil CO_2 level. According to the results of his experiment, the root systems of *A. deserti*, *Ferocactus acanthodes*, and *Opuntia ficus-indica* could survive for many days in anoxic soil conditions, but the root cells of the three species lost their viability as the soil CO_2 level ascended.

Soil Water and Agave Growth

Soil water availability to plants depends highly upon properties of the plant, i.e., root properties and physiological responses to water stress; and properties of the soil, including hydraulic conductivity, hydraulic diffusivity, matric potential, and wetness (Hillel, 1982). Soil water availability to desert succulents must be considered in terms of the acquisition of water from the soil and the prevention of water loss from the plant roots. The latter, especially, is a crucial factor for desert succulents to survive in arid and semiarid regions.

Water flows from high potential to low potential in the soil. In the interface between root surfaces and the soil, the same water movement occurs; that is, if soil water potential is higher than the root cell water potential, water flows from soils into roots. This normally happens in humid regions, but in contrast soil water potential is much lower than root water potential during the dry season in arid and semiarid regions. Most plants have difficulty surviving in such a soil water status. During drought, however, desert succulents prevent water loss by adjusting water movement from roots to soil with decreasing soil water potential (Nobel and Sanderson, 1984; Jordan and Nobel, 1984; Lopez and Nobel, 1991).

The rate of radial water flow out of roots to the soil (root hydraulic conductivity) in desert succulents decreases when soil water potential declines, so desert succulents can maintain fleshy leaves and stems during drought (Nobel and Sanderson, 1984). Jordan and Nobel (1984) reported that the decrease of root hydraulic conductivities of *Agave deserti* and *Ferocactus acanthodes* begins when soil water potential declines below -0.6 MPa and -1.3 MPa.

Lopez and Nobel (1991) investigated the responses of the root hydraulic conductivities of two cactus species to root age, root temperature, and soil water potential. They found that 1) the root hydraulic conductivities of *F. acanthodes* and *Opuntia ficus-indica* increased with root age from 1-3 weeks to 11-17 weeks and then declined with root age, 2) the root hydraulic conductivities of 1-3 week and 8 week roots for both species were maximized at 10 °C and 40 °C soil temperature, respectively, and those of older roots increased as root temperature rose from 0 °C to 50 °C, and 3) the decreasing rate of root hydraulic conductivity as soil water potential was reduced depended upon root age

Soil water availability to agaves highly depends upon soil texture. Agaves occur in well-drained soils (Gentry, 1982; Nobel, 1988). Well-drained soils such as sandy soils retain less water than clayey soils at any particular matric potential due to relatively large pore size (Hillel, 1982). According to Nobel (1988), however, sandy soils provide more available water to agaves than clayey soils due to high water retention at high soil water potential: since the leaf water potential of agaves is about -0.3 MPa under wet conditions, and the water contents by volume of a sandy soil at field capacity (-0.01 MPa) and -0.3 MPa are 30% and 8%, respectively. Since those of a clayey soil are 40% and 32%, 22% of water is available in the sandy soil, while the available water percentage of the clayey soil is only 8% after a heavy rainfall.

The rapid occurrence of ephemeral rain roots from the established roots of agaves after rainfall helps take up available water from the soil to recharge water in the water storage tissue (Nobel and Sanderson, 1984; Nobel, 1988). The recharge of water storage occurs within one week, and 87% of water absorbed by roots is stored (Schulte and Nobel, 1989).

Agaves have effective morphological and physiological mechanisms to maintain water balance in tissue during drought and to take up water from porous sandy soils which tend to be well-drained after rainfall.

Soil Temperature and Agave Growth

Soil temperature greatly influences soil biological, chemical, and physical activity in the root zone of plants; for example, water and nutrient uptake by plants, root nodulation and nitrogen fixation by microorganisms, water movement, and chemical reactions (Glinski and Lipiec, 1990; Paul and Clark, 1989; Hillel, 1982; Bohn et al., 1985). These activities directly affect plant growth; that is, there is an optimum soil temperature for growth in each plant. Root elongation rates are used as a parameter to determine the optimum soil temperature for plant growth leading to maximum root elongation rate. For example, optimum soil temperature is 20 °C for sunflower (*Helianthus* sp.) (Galligar, 1938) and 30 °C for maize (*Zea mays*) (Anderson and Kemper, 1964) and tomato (*Lycopersicon esculentum*) (White, 1937).

The effect of soil temperature on the root growth of agave was studied by Jordan and Nobel (1984). They reported that root elongation of *Agave deserti* reached a maximum at a soil temperature of about 30 °C, and 50% of root cells stopped their function at a soil temperature of -7 °C and 56 °C. There are no available soil temperature data for other species of agave. As described in the previous section, soil temperature also affects water uptake by roots of desert succulents (Lopez and Nobel, 1991).

Soil surface temperature is crucial for seedling establishment of agaves in arid regions (Jordan and Nobel, 1979). In fact, seedlings of saguaro (*Carnegiea gigantea*) often occur under desert trees and shrubs which supply shading at the Saguaro National Monument, Arizona (Turner et al., 1966), and no seedlings of *A. deserti* naturally occur in the field at Agave Hill, California (Nobel, 1977b). According to the field observations by Nobel (1984a), 52% of the seedlings of *A. deserti* under less than 50% shading provided by mature agaves, other plants, and rocks, experienced high temperature damage in the field at Agave Hill whose maximum soil surface temperature was 68 °C in the late summer. On the other hand, only 14% of the seedlings were damaged under more than 50% shading. He concluded that shading is necessary for seedling establishment of *A. deserti* in places where soil surface temperature reaches an extremely high level.

Nutrients and Agave Growth

In the past, detailed studies on the responses of agaves to nutrients were restricted to a few commercially successful species, which are *Agave sisalana* (sisal) and *A. foucroydes* (henequen) (Azancot de Menezes, 1963; Jesus Munoz Vazquez, 1968; Lock, 1969; Pinkerton, 1971). These research results suggest that nitrogen (N), phosphorous (P), potassium (K) and calcium (Ca) facilitate agave growth, and the deficiency of boron (B), iron (Fe), and manganese (Mn) severely retard agave growth.

N is the primary nutrient for the growth of leaves, heads, and roots of *A. sisalana*, and then P, while K and Ca contribute to the increase of dry matter of heads and roots but not to leaves (Lock, 1969). Ca plays an important role in the root development of *A. sisalana* (Lock, 1969). The fiber of *A. foucroydes* improves both in quality and in quantity in soils rich in Ca (Jesus Munoz Vazquez, 1968). The symptoms of B deficiency develop in *A. sisalana* when the B level of leaf tissue drops to less than 12 ppm (Lock, 1969). This suggest that *A. sisalana* has a high requirement of B.

Pinkerton (1971) examined micronutrient deficiencies in *A. sisalana* through water culture. He observed severe retardation of root and leaf growth caused by B deficiency and the markedly slow unfolding of leaves due to Fe and Mn deficiencies. He noted that since *A. sisalana* showed mild symptoms of B deficiency in the complete nutrient treatment whose B level was 0.25 ppm on occasion, it requires a relatively high amount of B. The symptoms disappeared at a B solution level of 2 ppm, and the growth impediment did not occur when 5 ppm B was applied.

The responses of a wide range of agave species to elements were examined by Nobel and Berry (1985). Their experimental results agreed with previous research. The six agave species used were *A. americana*, *A. deserti*, *A. foucroydes*, *A. lechuguilla*, *A. salmiana*, and *A. utahensis*. The growth parameter used in their experiment was nocturnal acid accumulation in leaf tissue. Nocturnal acid accumulation indicates the metabolic activity of CAM photosynthesis; for example, high nocturnal acid accumulation means high productivity. They suggested that N can be the most limiting element for the growth of the six agave species. Because the correlation coefficient of nocturnal acid accumulation to N level in the tissue of six species was 0.70, and that of N level in the tissue to N level in the soil from the root zone of six species was 0.53. And both correlation coefficients for N were the highest of all elements. The next highest correlation with nocturnal acid accumulation was B (r^2 = 0.51) and then Ca (r^2 = 0.46). They were in agreement with Lock (1969) on the effect of P and K: the correlation coefficient between P and K levels in the tissue and nocturnal acid accumulation was less than 0.12.

As for the responses to Ca, Nobel and Berry (1985) reported that the growth rate of roots and shoots of seedlings of *A. deserti* were reduced at both extremes of Ca levels in sand culture, but showed little difference in the wide range of solution Ca levels from 8 ppm to 200 ppm. And they found that agaves occured in the soil which has the wide range of Ca (149 ppm to 7130 ppm). They concluded that applications of Ca had no marked influence on the growth of agaves. In the meantime, the tissue of mature agaves contained a relatively high amount of Ca in comparison to other crops: Ca level is 2% for other crops, 5.2% to 7.0% for *A. lechuguilla* (the highest in the six species), and 2.1% to 2.5% for *A. utahensis* (the lowest in the six species). The interpretation by Nobel and Berry concerning the relatively high Ca accumulation in agave leaves is not clear. The Ca accumulation in tissue with age also occurs in cacti, which are desert succulents and exhibit CAM photosynthesis (Nobel, 1983b). The responses of agaves to Ca may explain why agaves tend to occur in the soils which contain limestone (Table 2).

With regard to other elements, Nobel and Berry (1985) found that the seedlings of *A. deserti* exhibited a high tolerance to B, copper (Cu), and zinc (Zn). According to their results, root and shoot growth of seedlings were little influenced at B levels less than 3.3 ppm, but root elongation was suppressed to 50% at 0.7 ppm Cu and 7.8 ppm Zn, while shoot growth showed no reduction under these same conditions.

There is a general consensus among researchers who studied the effect of B on agaves that B contributes to the productivity of agaves (Lock, 1969; Pinkerton, 1971; Nobel and Berry, 1985). This suggests that agaves tolerate high soil B levels. The same positive response to B as agaves was verified in several species of cacti (Berry and Nobel, 1985; Nobel et al., 1987). Berry and Nobel (1985) reported the high B tolerance of *Opuntia ficus-indica* and *Ferocactus acanthodes* whose photosynthetic pathway is CAM. Nobel et al. (1987) also reported that *O. engelmannii* and *O. rastrera* which are prickly pear cacti showing CAM metabolism also exhibited positive responses to high levels of soil B: the productivity of these cacti was highly correlated with soil B levels ($r^2 = 0.66$). B toxicity is common in arid region soils, and the growth impediment caused by B toxicity usually occurs in sensitive plants at a few ppm B in the soil solution (Bohn et al., 1985; Knight, 1991).

Nobel and Hartsock (1986b) observed the optimum level of soil N for the growth of *A. deserti*. According to their results, shoot and root dry matter weight of seedlings of *A. deserti* increased with increasing levels of soil N up to about 0.1% by soil dry weight in sand culture. And when 100 kg N ha^{-1} was added to the soil, the rate of leaf unfolding of mature plants increased with increasing soil N level and reached the highest point, which is twice as much as the rate under natural conditions. Their experimental results, however, showed that levels of soil N higher than the amount of N at the highest growth rate hindered agave growth.

Nobel and his colleagues (1988) examined the growth responses of *A. deserti* and *A. lechuguilla* to N, P, K, and B under field conditions. Two species were grown and examined in different places; *A. deserti* near Palm Desert, California, U. S. A. and *A. lechuguilla* in Saltillo, Coahuila, Mexico. The response of *A. deserti* to N was the same as the previous study by Nobel and Hartsock (1986b). The number of expanded leaves per plant of *A. deserti* was highest at a soil N level of 100 kg ha^{-1}. On the other hand applications of P (up to 300 kg ha^{-1}), K (up to 1000 kg ha^{-1}), and B (up to 100 kg ha^{-1}) did not significantly increase the rate of leaf unfolding. According to their explanation, the cause of no apparent response of *A. deserti* to the three elements is due to high levels of those three elements in the soil of the *A. deserti* site, which originally contained 35-73 ppm P, 109-147 ppm K, and 1.07-1.65 ppm B. *A. lechuguilla* also exhibited similar response to N as *A. deserti* did at 100 kg N ha^{-1}, but the lower rate of leaf expansion compared with *A. deserti* owing to high N level in the original soil; the % soil N of *A. lechuguilla* site is 0.046-0.070, and that of *A. deserti* site is 0.220-0.272. Unlike *A. deserti* the species apparently responded to the application of the other three elements in the soil whose three nutrient levels are 18-28 ppm P, 28-36 ppm K, and 0.42-0.54 ppm B. The number of expanded leaves per plant of *A. lechuguilla* when 500 kg P ha^{-1} was added to the soil, was a match for levels of enhancement by the addition of 100 kg N ha^{-1}. Applications of 500 kg K ha^{-1} and 100 kg B ha^{-1} also increased the number of expanded leaves per plant. Nobel and his colleagues concluded that the addition of N, P, K, and B improve the growth of agaves, and the degree of effectiveness depends upon the original levels of those elements in the soil.

Organic matter content in the soil is one of the parameters by which soil fertility is evaluated and an important nutrient source for plant growth. Generally, plants grow vigorously in soils enriched with organic matter as it improves physical and chemical soil properties (Hillel, 1982; Bohn et al., 1985). In *A. sisalana* culture in Tanzania, organic matter is also constantly supplied to topsoils to maintain soil fertility (Lock, 1969). In Mexico, the fibre quality of *A. foucroydes* , however, is lowered in soils rich in organic matter (Jesus Munoz Vazquez, 1968). There is apparently no new research concerning the effect of organic matter on the growth of agaves.

Hydrogen Ion Concentration (pH) in Soil and Agave Growth

Soil pH affects plant growth through its influence on nutrient availability to plants, concentrations of toxic materials to plants in the soil solution, and microbial activities (Tisdale et al., 1985). Ammonium-ion fixation by expanding silicate minerals decreases with decreasing soil pH, and both high and low pH levels cause phosphate fixation because phosphate forms insoluble compounds with Fe and aluminum (Al) at low pH and with Ca at high pH (Bohn et al., 1985). Low soil pH induces the release of toxic elements and the deficiency of nutrients: for example, Al toxicity, Mn toxicity, Ca deficiency, and molybdenum (Mo) deficiency (Singer and Munns, 1987). The activity of nitrification bacteria decreases at soil pH less than 5.5 (Paul and Clark, 1989).

Seeds require water, temperature, and oxygen for germination, which is the first crucial step for plant establishment. The effect of pH on seed germination of agaves was studied by Freeman (1973 and 1975) and Jordan and Nobel (1979). Freeman (1973) examined the germination responses of seeds of *A. lecheguilla* at various levels of pH. According to his laboratory tests, the best percent germination occurred at pH 6.15, and a decline of percent germination occurred at pH 7.30 and 7.85. These laboratory results, however, did not agree with the distribution of *A. lecheguilla* in nature: as observed by Freeman where, the species were mostly found in soils whose pH ranges from 7.8 to 8.5, with the lowest soil pH value where he found the species was 7.2. The germination response of *A. parryi* to pH was also examined by Freeman (1975). He reported that seeds of *A. parryi* showed the best germination at a pH of about 7.5 five days after the test started, but no significant differences in percent germination was found in the pH range from 7.0 to 8.5 after eight days. Jordan and Nobel (1979) reported that seeds of *A.deserti* could germinate uniformly over a broad pH range from 4.1 to 9.7. Thus, agaves germinate in a wide range of pH levels. The results of these studies on the germination responses of agaves to pH suggest that soil pH has no major effect on the restriction of seed germination of agaves (Nobel, 1988).

With reference to seedlings of agaves, the insensitivity of seedlings to pH was confirmed by Nobel and Berry (1985). The results of their long term sand culture experiment (6 months) showed that no significant differences occurred in the root and shoot growth of seedlings of *A.deserti* in the pH range from 4.5 to 8.5. However, Nobel and Hartsock (1986b) observed a narrower unaffected pH range than the pH range in sand culture when seedlings of *A. deserti* were grown in the soil from the field where the species occur in nature. According to them, root and shoot of seedlings of *A. deserti* grew well in soils whose pH ranges from 6 to 8, and this pH range accorded with the pH range of the root zone of the species in the natural habitats, which is from 6.1 to 8.2. Meanwhile, they also reported that seedlings were killed at soil pH levels of about 5 two months after germination, with no seedlings surviving for six months. In alkaline soils whose pH is 9, seedling growth declines only 28% in shoot and 6% in root in comparison to the growth at pH 6 to 8 (Nobel and Hartsock, 1986b; Nobel, 1988). The difference of the responses of seedlings to pH between sand culture and culture in soil would be due to the difference of nutrient availability to seedlings in the sand culture and the soil (Nobel, 1988). In the soil, low pH such as pH 5 would cause low nutrient availability to plants.

Acid soils qualitatively and quantitatively cause damage to *A. sisalana* and *A. foucroydes* cultures (Jesus Munoz Vazquez, 1968; Lock, 1969). A. sisalana has been grown in the soils whose pH ranges from 4.5 to 8 in Tanzania, but the species clearly shows the symptoms of Ca, P, K, and Mg deficiencies at pH 4.5 (Lock, 1969). Liming is essential for *A. sisalana* culture in Tanzania when soil pH is below 6 (Lock, 1969). *A. foucroydes* culture in Yucatan, Mexico, has been carried out in the soils whose pH ranges from 7.1 to 8.9 (Sprague et al., 1978). From the results of laboratory experiments and field observations, the soil pH range from 6 to 8 seems to provide healthy growth of agaves in nature and cultivated lands (Nobel, 1988).

Salinity and Agave Growth

Saline soils contain a large quantity of soluble salts, which are commonly Na, Ca, and Mg, with Cl, SO_4, and HCO_3 (Singer and Munns, 1987). These soils are common in arid and semiarid regions because low annual precipitation is insufficient to leach salts, and they will accumulate in the soil (Bohn et al., 1985; Knight, 1991). Salt accumulation in the plant root zone induces a serious reduction of yield due to insufficient water uptake by plants from the salty soil solution (Ayers and Westcot, 1989). The degree of soil salinity has been usually described in terms of electrical conductivity (EC) of the saturated paste extract solution because of the quickness and acceptable accuracy of the measurement (Bohn et al., 1985).

With regard to the responses of CAM plants to salinity, pinapple (*Ananas comosus*) shows moderately tolerance to salinity and can be grown in the soil EC range from 3.0 dS m^{-1} to 6.0 dS m^{-1} (Ayer and Westcot, 1989). However, generally, the absorption of nutrients from the roots of most CAM plants deteriorates substantially in high saline soil (Winter, 1985). CAM plants show certain behavior characteristics for survival that are related to the maintenance of their moisture uptake and storage systems under saline conditions. Succulent leaves are not only water storage receptacles to prevent tissue dehydration but also serve as an organ to reduce salt concentrations (Crawford, 1989). Some succulents send salts to their aging leaves and remove salts by shedding those aging leaves (Crawford, 1989). *Pereskia guamacho* sheds its highly succulent leaves to avoid stress caused by drought and salinity during the dry season in coastal habitats of Venezuela (Luttge et al., 1989). In the same place, *Opuntia wentiana* grows only during the rainy season when a heavy rainfall washes salts away (Medina et al., 1989). Thus, CAM plants generally appear to be intolerant to salinity, and some of them have physiological mechanisms for survival in saline conditions. The tolerance of plants to salinity has no correlation with photosynthetic pathways such as C_3, C_4, and CAM and depends upon an individual plant species (Ayers and Westcot, 1989).

According to Ayers and Westcot (1989), barley is the most salinity tolerant crop and yields 100% at soil EC level of 8.0 dS m^{-1}. Its growth stops at EC 28 dS m^{-1}. But on the other hand even though the EC value for 100% yield of Date palm is lower than that of barley, its critical EC for growth is 32 dS m^{-1} and the highest of all crops listed by them. Table 3 provides the EC values for 100% and 0% yield for ten agronomic plants and *Agave sisalana*. According to Table 3, the EC for 0% yield of *A. sisalana* is 23.4 dS m^{-1} which places it within the EC range for 0% yield of salt tolerant crops such as barley, cotton, date palm, and wheat. The EC for 100% yield for *A. sisalana* is 0.62 dS m^{-1}. This value was recorded at the Marana Agricultural Center, Tucson, Arizona, where *A. sisalana* was experimentally grown (Nobel and McDaniel, 1988). A. sisalana also appears to prefer soils low in soluble salts as other agronomic plants do.

As for the responses of other agave species to EC, Table 4 shows the EC values of the root zone of six agave species which were estimated from the data of Nobel and Berry (1985). Soils were collected from fields where agaves are growing except for the greenhouse soil of *A. americana*. From Table 4, *A. americana*, *A. foucroydes*, *A. lechuguilla*, and *A. salmiana* grow in highly saline soils: especially, *A. foucroydes* which can grow in soils whose estimated EC ranges from 44 dS m^{-1} to 47 dS m^{-1}. High EC values are due to high Ca content in the soils (Table 4). There were no reports about the damage by high soil Ca in the paper of Nobel and Berry (1985). On the contrary, the productivity of agaves in the fields where the soils were collected are high enough for commercial production: the productivity in dry matter weight is 1.60 kg m^{-2} $year^{-1}$ for *A. foucroydes* (Nobel, 1985), 0.38 for *A. lechuguilla* (Nobel and Quero, 1986), and 1.05 for *A. salmiana* (Nobel and Meyer, 1985).

With regard to sodium (Na) toxicity, Nobel and his colleagues (1984) found that nocturnal CO_2 uptake and nocturnal acid accumulation in *Cereus validus*, which is a cactus showing CAM, were inhibited 67% and 49%, respectively, in the soil treated with 9196 ppm of NaCl for 14 days. Nobel and Berry (1985) reported that a 50% decrease occurred in the root elongation of seedlings of *A. deserti* when the concentration of NaCl in the hydroponic solution was 1287 ppm. The root growth disturbance by high concentration of Na was also recorded in *Opuntia humifusa*, which is a platycactus exhibiting CAM (Silverman, Young, and Nobel, 1988). Low metabolic function and the decrease of root elongation would be due to Na toxicity, but McDaniel (personal communication, 1992) suggests the possibility of chloride (Cl) toxicity.

Previous research suggests that saline soil due to high Ca does not affect agave growth, but saline soil due to Na inhibits agave growth. The diagnosis of the effect of salinity on agave growth should be carried out by not only EC but also the Na content in the soil.

Table 3. Salinity tolerance of crops[a].

Crop	EC for 100% yield	EC for 0% yield[b]
Barley (*Hordeum vulgare*)	8.0 (dS m^{-1})	28 (dS m^{-1})
Cotton (*Gossypium hirsutum*)	7.7	27
Wheat (*Triticum aestivum*)	6.0	20
Soybean (*Glycine max*)	5.0	10
Rice (*Oliza sativa*)	3.0	11
Corn (*Zea mays*)	1.7	10
Potato (*Solanum tuberosum*)	1.7	10
Carrot (*Daucus carota*)	1.0	8.1
Lettuce (*Lactuca sativa*)	1.3	9.0
Date palm (*Phoenix dactylifera*)	4.0	32
Agave sisalana[c]	0.62	23.4

[a]. Crops except for *A. sisalana* were selected from data of Ayers and Westcot (1989). Soils were collected from root zones, and EC was measured using the saturation extract of the soil (Ayers and Westcot, 1989).

[b]. 0% yield means that crop growth stops (Ayers and Westcot, 1989).

[c]. 0.62 dS m^{-1} and 23.4 dS m^{-1} of *A. sisalana* were cited from the results chemical analysis of the Marana soil in this current research (1992) and Lock (1969), respectively. 23.4 dS m^{-1} was converted from1.5% soluble salts in the surface soil (Lock, 1969). The conversion formula is as follows: 1.5g soluble salts/100g soil = 15,000g soluble salts/1,000,000g soil, and conversion factor is 640 (Rhoades, 1982), hence, 15,000ppm soluble salts/640 = 23.4 dS m^{-1}

Table 4. Range of Na, Ca, Mg, estimated EC, and sodium absorption ratio (SAR) of soils from the root zones of six agave species[a].

Species	Na (ppm)	Ca (ppm)	Mg (ppm)	Estimated EC[b] ($dS\ m^{-1}$)	SAR[c]
A. americana[d]	133-155	950-1110	125-135	7.0-8.0	5.7-6.2
A. deserti	29-67	149-185	82-176	1.8-3.0	2.7-5.0
A. foucroydes	77-83	6590-7130	448-500	44-47	1.3
A. lechuguilla	41-59	3030-3630	30-32	17-20	1.0-1.4
A. salmiana	68-80	2300-2760	86-98	13-16	2.0-2.1
A. utahensis	24-64	210-262	130-150	2.5-3.2	1.8-4.5

[a]. Data of Na, Ca, and Mg were cited from Nobel and Berry (1985). Soils were extracted with 1N ammonium acetate at pH 7.

[b]. The EC values were calculated using the following equation:

$$\log C = 0.926 + 1.037 \log Lm \quad (r^2 = 0.9998)$$

where C (me l^{-1}) is the sum of NaCl, $CaCl_2$, and $MgSO_4$, and Lm is conductivity ($dS\ m^{-1}$) (Marion and Babcock, 1976).

[c]. SAR = Na/(SQR ((Ca+Mg)/2)) (U.S. Salinity Laboratory Staff, 1954)

[d]. This species was grown in the greenhouse soil.

Productivity of Agaves

The productivity of agaves is highly influenced by annual rainfall, and generally high productivity is recorded where annual rainfall is more than 1000 mm (Nobel, 1990b). The productivity of *Agave tequilana* at sites in Tequila, Jalisco, Mexico, is 2.11 kg m^{-2} $year^{-1}$ to 2.49 kg m^{-2} $year^{-1}$, where annual rainfall is about 1080 mm (Nobel and Valenzuela, 1987). *A. lechuguilla* produces 0.38 kg m^{-2} $year^{-1}$ in the field near Saltillo, Coahuila, Mexico, where average annual rainfall is 375 mm (Nobel and Quero, 1986).

A. salmiana, however, exhibits high productivity, 1.05 kg m^{-2} $year^{-1}$, at a site in Salinas de Hidalgo, San Luis Potosi, Mexico, under about 400 mm of average annual rainfall (Nobel and Meyer, 1985).

Environmental productivity index (EPI) introduced by Nobel (1984b) is a reliable parameter for predicting net productivity of agaves in the field. According to him, EPI is determined by the responses of net CO_2 uptake by agave to soil water availability, ambient temperature, and solar radiation. He defines these three environmental variables as a "water index", a "temperature index", and a "photosynthetically active radiation (PAR) index" and expresses EPI as the product of three indices.

Each index value is obtained as the fraction of the value of each environmental parameter which induces maximum net CO_2 uptake per unit leaf area to each index; for example, the temperature index is 1.00 when day/night air temperature is 25°C/15°C which induces maximum net CO_2 uptake, and the index decreases to 0.80 when net CO_2 uptake is reduced 20 % at 18°C/8°C compared with the maximum net CO_2 uptake (Nobel, 1984b, 1988). Nobel (1984b) found that there was a high correlation between number of new leaves of *A. deserti* and EPI ($r^2 = 0.93$), and also between water status index and EPI ($r^2 = 0.97$). EPI is defined as the following equation:

$$\text{EPI} = \text{Water index} \times \text{Temperature index} \times \text{PAR index (Nobel, 1988).}$$

The form of the equation is multiplication because when one of three indices becomes zero, the occurance of net CO_2 uptake will be totally controlled even though the other indices are a maximum value of 1.00 (Nobel, 1988). The high correlation between EPI and the number of new expanded leaves of agaves were reconfirmed in several places of Mexico: *A. foucroydes* in Yucatan (r^2 = 0.85) (Nobel, 1985), *A. salmiana* in San Luis Potosi (r^2 = 0.95) (Nobel and Meyer, 1985), *A. lechuguilla* in Coahuila (r^2 = 0.83) (Nobel and Quero, 1986), and *A. tequilana* in Jalisco (r^2 = 0.81 for 1-year old plant, r^2 = 0.94 for 3-year old plant, and r^2 = 0.93 for 6-year old plant) (Nobel and Valenzuela, 1987).

Nobel (1989) proposed a "nutrient index" (NI) which is the product of N, P, K, B, and Na indices as an additional multiplicative factor in EPI. He defines NI as follows:

$$\begin{aligned} NI &= N\ \text{index} \times P\ \text{index} \times K\ \text{index} \times B\ \text{index} \times Na\ \text{index} \\ &= (1.418+0.348\ln N) \times [1+0.195\ln(P/60)] \times [1+0.117\ln(K/250)] \\ &\quad \times B^{0.213} \times (1-0.00288Na) \end{aligned}$$

where the unit of N is % of dry soil, and those of P, K, B, and Na is ppm of dry soil. All constants were determined according to the levels of each element which lead to the maximal growth and the zero growth based on data from previous research (Nobel, 1983b, 1988; Nobel and Berry, 1985; Nobel and Hartsock, 1986b; Nobel, Quero and

Linares, 1988; Nobel et al., 1984, 1987; Silverman, Young, and Nobel, 1988). Maximal values of N, P, K, and B to lead the growth of agaves to a maximum point when Na is zero are; N is 0.3%, P is 60 ppm, K is 250 ppm, and B is 1.0 ppm (Nobel, 1989, 1990b). An acceptable level of soil Na is about 150 ppm, which leads Na index to 0.568 (Nobel, 1989, 1990b).

NI was highly correlated with the number of expanded leaves annually per plant of *A. tequilana* ($r^2 = 0.96$) at sites near Tequila, Jalisco, Mexico (Nobel, 1989). However, Nobel (1990b) found that NI did not predict the growth responses of *A. victoriae-reginae* to high soil K levels, and the inhibition of the growth by increasing Na levels was unexpectedly high. He suggests that further investigation of the effect of high soil K levels on the growth of agaves is necessary for a modification of NI, and the coefficient of Na index, 0.00288, must be changed.

3. MATERIALS AND METHODS

Study Site Description

Nine study sites were chosen from five areas in southeastern Arizona: they are Marana, Avra Valley, Page Ranch, Texas Canyon and Safford. In Texas Canyon, five representative sites were selected based on the distribution of native population of *Agave palmeri*. The other four places had one representative site. The University of Arizona Branch Experiment Station was chosen in the Marana, Safford, and Page Ranch areas. The study site of Avra Valley is abandoned cotton fields. Geographical information of nine sites is given in Table 5.

Table 5. Locations of study sites.

Site	Latitude	Longitude	Altitude (m)
Marana	32° 28' N	111° 13' W	600
Avra Valley	32° 14' N	111° 17' W	610
Page Ranch	32° 37' N	110° 52' W	1146
Texas Canyon Walnut Wash, North Saddle	32° 05' N	110° 03' W	1469
Texas Canyon Walnut Wash, South Saddle	32° 05' N	110° 03' W	1469
Texas Canyon Adams Peak, North	32° 02' N	110° 06' W	1439
Texas Canyon Adams Peak, South	32° 02' N	110° 06' W	1439
Texas Canyon Triangle T Ranch	32° 02' N	110° 05' W	1445
Safford	32° 49' N	109° 41' W	900

The study sites of Marana and Safford are cultivated lands, and those of the other three places are uncultivated lands. Figure 2 is the map which indicates their locations.

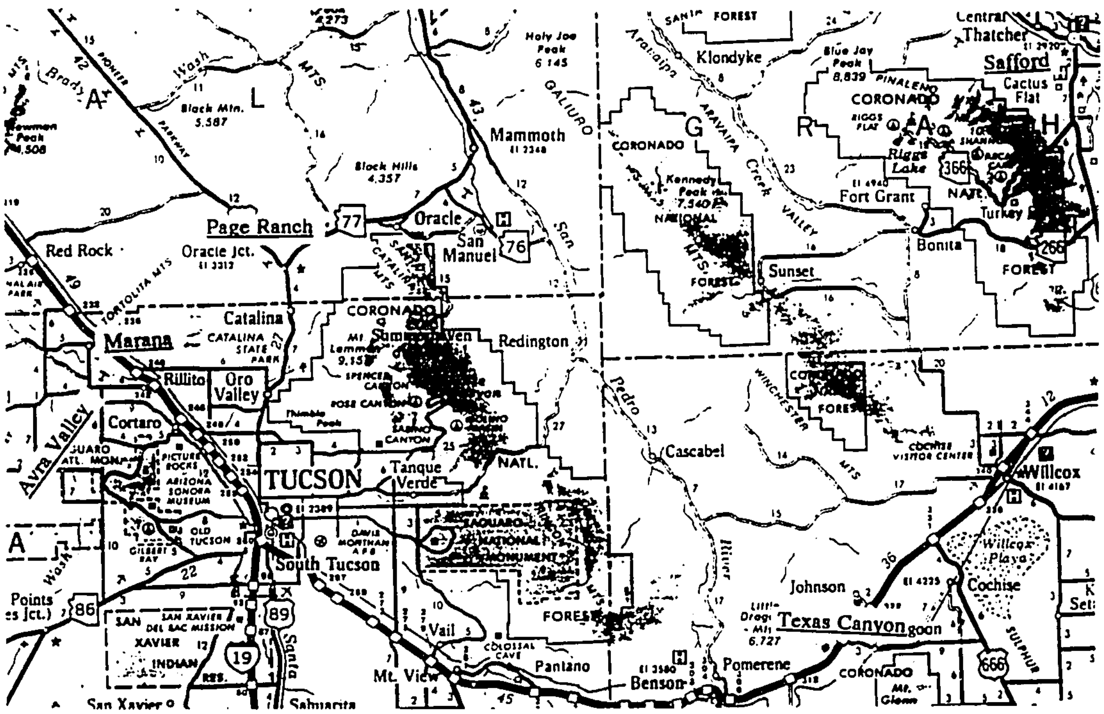

Fig. 2. Map showing study sites

Figure 3-9 shows the appearance of study sites. Desert grasslands occur in the Page Ranch area. Desert scrub is found in the desert of the Avra Valley area. Texas Canyon, Adams Peak and Triangle T Ranch sites are stony and rocky, and desert grassland and mountain meadows develops in the stony and rocky slopes. Soils of Texas Canyon Walnut Wash site contain a lot of weathered granitic cobbles and gravel, and desert grasslands develop in this area.

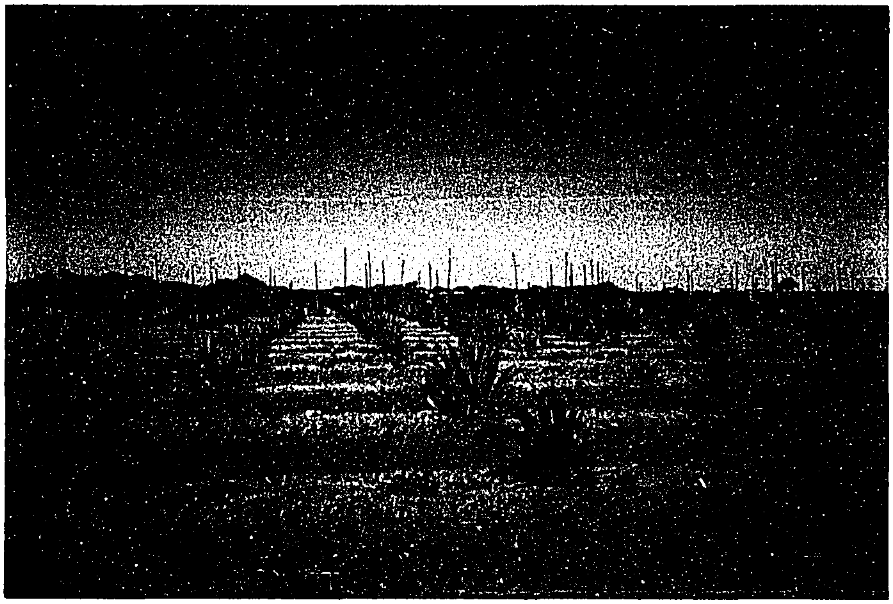

Fig. 3. A view of the Marana study site.

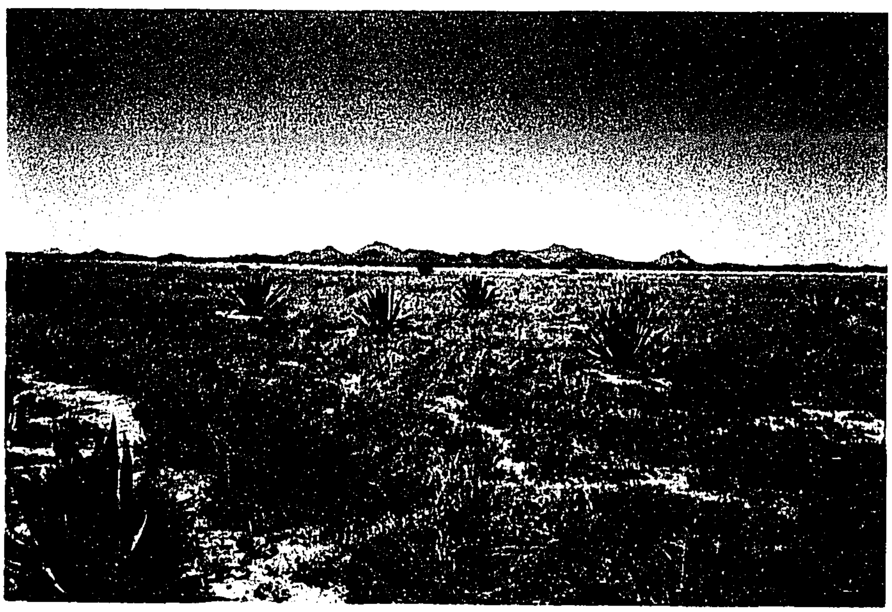

Fig. 4. A view of the Avra Valley study site.

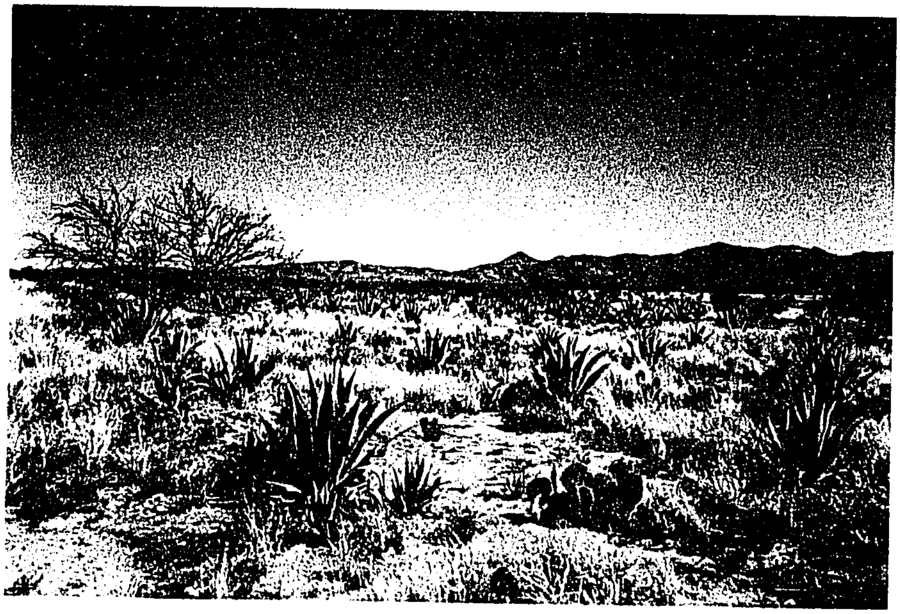

Fig. 5. A view of the Page Ranch study site.

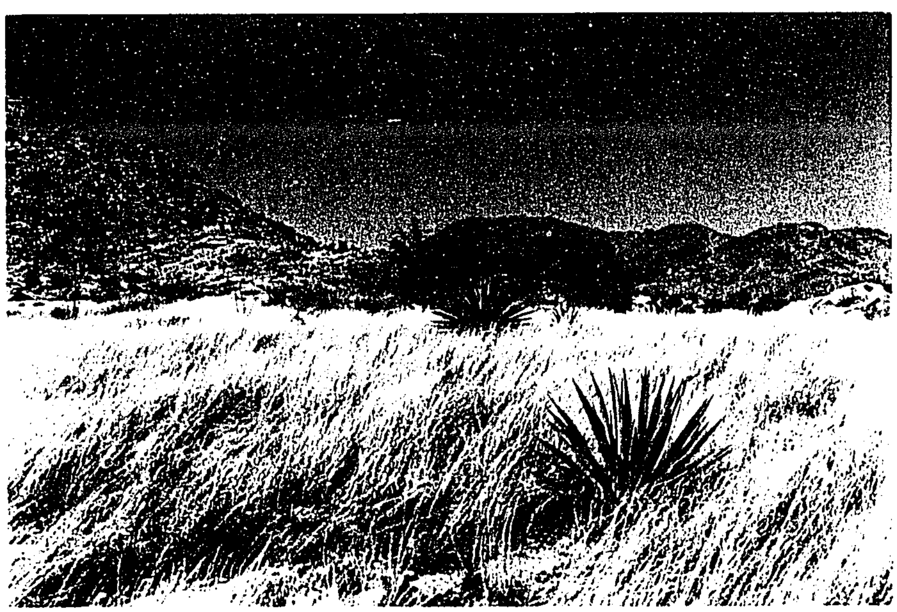

Fig. 6. A view of the Texas Canyon, Walnut Wash study site.

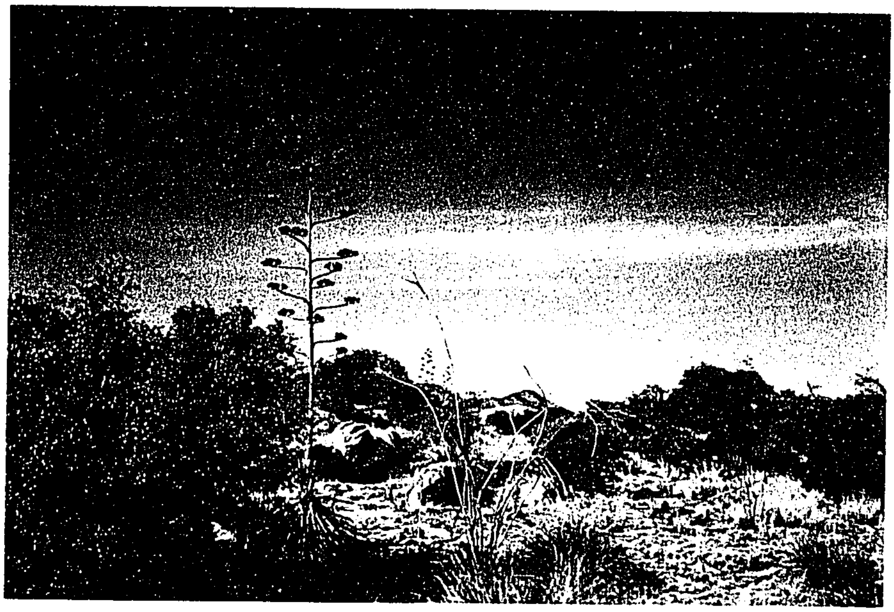

Fig. 7. A view of the Texas Canyon, Adams Peak study site.

Fig. 8. A view of the Texas Canyon, Triangle T Ranch study site.

Fig. 9. A view of the Safford study site.

According to the Arizona General Soil Map (Hendricks, 1985), the Avra Valley soil is within the Hyperthermic Arid soils mapping unit, characterized by a mean annual precipitation of 150 to 280 mm and soil temperature of 22 to 27 °C in the 50 cm depth. Soils from the other study sites are the Thermic Semiarid soils, characterized by a mean annual precipitation of 250 to 460 mm and soil temperature of 15 to 22 °C. Detailed soil associations, mean annual precipitation and soil temperature of study sites are shown in Table 6.

Climatic Data

The climatic data shown in Figure 10 were obtained from air temperature and precipitation records for the Marana Agricultural Center cited in the paper by Nobel and McDaniel (1988) for the Marana field, the Arizona Sonora Desert Museum recorded in Arizona Climate: 1937-1972 (1974) for the Avra Valley field, and Oracle 2 SE, Willcox, and the Safford Agricultural Center reported in National Oceanic and Atmospheric Administration (NOAA) (1986-1990) for the Page Ranch, Texas Canyon, and Safford fields, respectively. Since there was no available climatic data in the Texas Canyon area, data of Willcox were used for the evaluation of agave growth. The elevation of Texas Canyon is higher than that of Willcox (approximately 1200 m), so there will be higher precipitation and lower air temperature in Texas Canyon than in Willcox (Hendricks, personal communication, 1992). Mean daily maximum and minimum air temperatures and mean daily precipitation averaged over a month in five observatories are shown in Figure 10.

Table 6. Soil associations, mean annual precipitation, mean annual soil temperature of study sites[a].

Site	Association	Mean annual precipitation (mm)	Mean annual soil temperature (°C)
Marana	Thermic semiarid soils, Torrifluvent Association	230 to 300	16 to 22
Avra Valley	Hyperthermic arid soils, Mohall-Vecont-Pinamt Association	150 to 280	22 to 27
Page Ranch	Thermic semiarid soils, White House-Caralampi Association	300 to 410	18 to 21
Texas Canyon Walnut Wash	Thermic semiarid soils, Nickel-Latene-Cave Association	250 to 360	18 to 22
Texas Canyon Triangle T R.	Thermic semiarid soils, Nickel-Latene-Cave Association	250 to 360	18 to 22
Texas Canyon Adams Peak	Thermic semiarid soils, Lithic Torriorthents-Lithic Haplustolls-Rock Outcrop Association	250 to 510	15 to 22
Safford	Thermic semiarid soils, Torrifluvent Association	230 to 300	16 to 22

[a]. All data were referred to Hendricks (1985).

Soil Analysis

Soil Sampling and Handling - Soil samples were collected by hand auger and shovel from a depth of 0 to 25 and 25 to 50 cm in the Marana, Avra Valley, and Safford study sites; 0 to

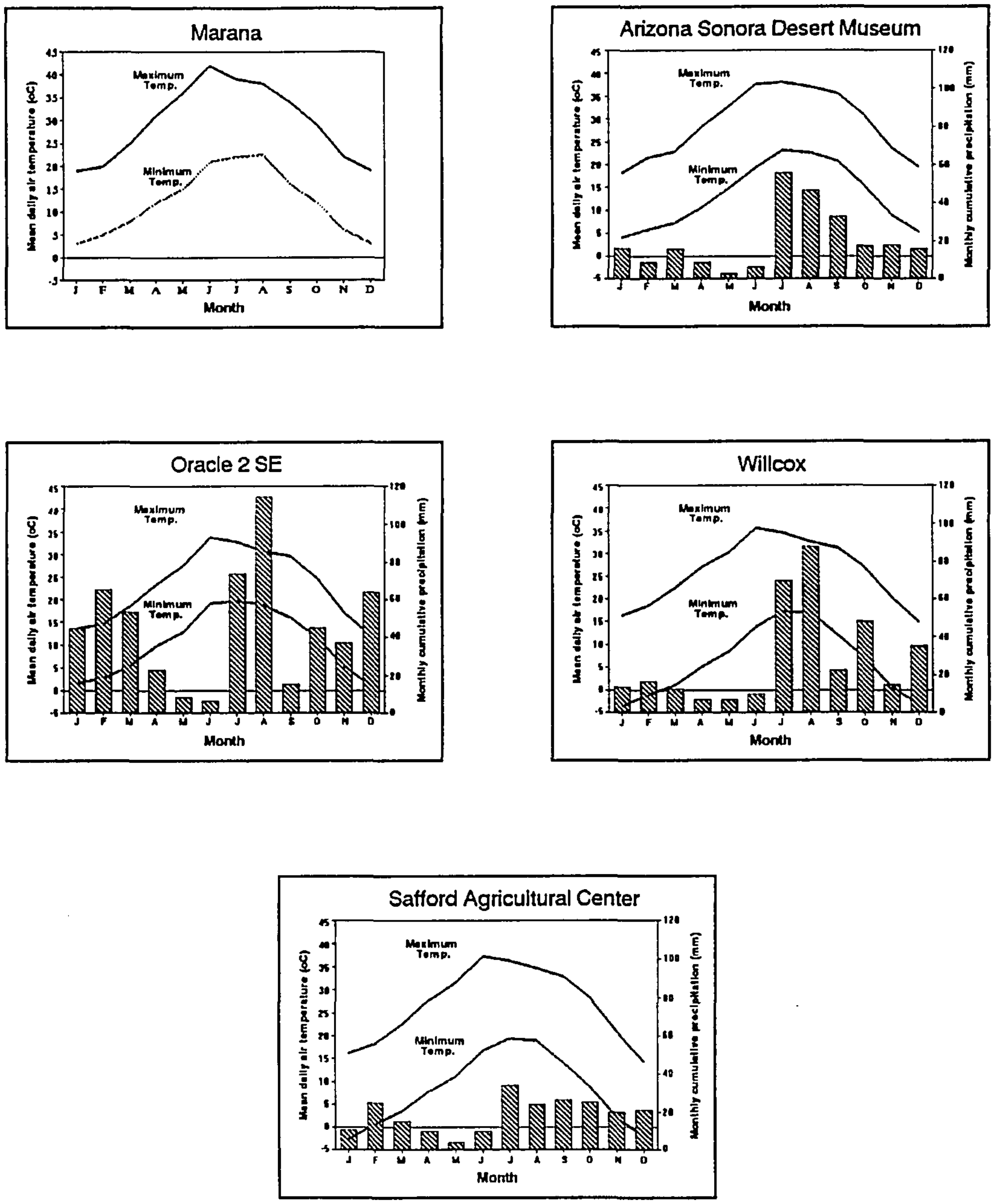

Fig. 10. Mean daily air temperature and monthly cumulative precipitation in five study areas.

10 and 10 to 25 in the Texas Canyon, Walnut Wash north and south saddles and Page Ranch study sites; surface in the Texas Canyon Adams Peak north and south and Triangle T Ranch study sites. Composite soil samples were collected from the above mentioned depths of each study site. Soil samples were dried in the greenhouse, weighed, and passed through a 2 mm mesh sieve. Coarse fragments were collected and weighed.

Soil Particle Size Analysis - The soil particle size analysis was determined by the hydrometer and sieve methods (Gee and Bauder, 1986). NaOH was used as a dispersing agent. Soils were stirred with a dispersing agent by a mixer for 4 minutes. Then, the clay content was determined by the hydrometer method, and sand content was weighed after washing soils through a 0.05 mm sieve. The content of silt was calculated by subtracting the sum of clay and sand from the total amount of soil. Sand was fractionated into five different particle size groups by using a nest of sieves. Soil texture classes were determined by using the USDA textural triangle.

Moisture retention at Permanent Wilting Point (PWP) - The moisture retention at PWP (-1.5 MPa) was measured using a pressure plate apparatus with high-range system (Klute, 1986). Soil samples were placed on the porous plate in a pressure chamber, and distilled water was added to the soil samples until the soils became oversaturated. Then, the pressure (-1.5 MPa) was added after the pressure chamber was closed. After 3 days, soil samples were removed from the chamber, weighed, and put in the oven (105 °C) for 24 hours. The dry soil samples were weighed, and the moisture content of soil samples were calculated.

Hydrogen Ion Concentration (pH) in Soil - A soil saturated paste was used for the determination of soil pH using a Fisher Scientific-made polymer electrode (Catalog No. 13-620-298) and Accumet Model 915 pH meter (Catalog No. 13-636-915 & 916).

Electrical Conductivity (EC) and Salts (Ca, Mg, Na, and K) - The EC value of a saturated extract solution of a soil sample was measured using YSI field/laboratory conductance meter of Yellow Springs Instrument Co., Inc. manufacture. The concentrations of salts in the saturated extract were determined by the intercouppled plasma emission (ICP) method. The ICP unit used was PS 1000 UV Purged Sequential ICP/Echelle Spectrometer in Leeman's PS Series.

Organic Carbon (Organic C) - Organic C was determined by the Walkely-Black wet combustion method (Nelson and Sommers, 1982). Organic matter was calculated from organic carbon by using the following conversion formula (Nelson and Sommers, 1982):

$$\% \text{ Organic matter} = 0.35 + (1.80 \times \% \text{ Organic C})$$

Biomass Data in Study Sites

All data were recorded by McDaniel from March 1980 to present (personal communication, 1992). The selection of agave species for the experiment was based on three criteria: 1) the ready availability of planting stock, 2) the anticipated adaptation of the species to the climate of the study sites available, and 3) a history of use of the species for alcohol production (McDaniel, personal communication, 1992). Agaves were grown by utilizing only water obtained from precipitation in the Page Ranch and Avra

Valley fields. The Marana and Safford fields were irrigated, and the total water supplied in both fields was approximately the same as the mean annual precipitation of the Page Ranch area.

In the Safford fields, the experiment which examined the tolerance of agaves to salinity was carried out from September 1980 to December 1986. *Agave americana* and *A. palmeri* were examined at three different levels of salinity in the irrigation water. Before the experiment was carried out, the leaching was performed in the field for the experiment. The soil sample which represents the Safford field was collected from the adjacent field. The final fresh weights of agaves in the lowest soluble salt concentration plot were used as biomass data of agaves in the Safford field in the context of the comparison with biomass data of the other study sites.

Agave species examined are shown in Table 7. Biomass data were recorded in all sites except for Texas Canyon. *A. palmeri* in Texas Canyon occurs in nature, so soil data of Texas Canyon are used for a description of soil characteristics of natural habitats of *A. palmeri* in the discussion section. Agave seedlings were transplanted at the four study sites in a grid pattern. Biomass data were recorded with fresh weights, which were determined in the fields for carefully excavated representative plants. Fresh weights included rhizomes and attached offshoots.

Greenhouse Experiment

This experiment was carried out in greenhouse of the Department of Plant Science at the University of Arizona from September 27, 1991, to Jannuary 24, 1992.

Table 7. Species of agave examined.

Site	Species	Cultivation period
Marana	*Agave americana*	Mar. 1980 - Mar. 1986
	A. deserti	Mar. 1986 - Mar. 1987
	A. fourcroydes	Aug. 1985 - May 1986
	A. murpheyi	Mar. 1985 - Mar. 1987
	A. palmeri	Mar. 1980 - Mar. 1986
	A. parryi	Mar. 1985 - Mar. 1987
	A. sisalana	Mar. 1985 - Mar. 1987
	A. vilmoriniana	Mar. 1985 - Mar. 1991
	A. weberi	Mar. 1985 - Mar. 1987
Avra Valley	*A. americana*	Mar. 1984 - Mar. 1989
	A. deserti	Mar. 1987 - Mar. 1989
	A. murpheyi	Mar. 1985 and 1986 - Mar. 1987
Texas Canyon	*A. palmeri*	Native population
Page Ranch	*A. americana*	Mar. 1981 - Mar. 1991
	A. palmeri	Mar. 1981 - present
	A. murpheyi	Mar. 1985 - 1986
Safford	*A. americana*	Sep./Oct. 1980 - Dec. 1986
	A. palmeri	Sep./Oct. 1980 - Dec. 1986

The Marana and Texas Canyon, Triangle T Ranch soils were used as representatives of clay loam and sandy loam soils, respectively, for the greenhouse experiment. About 10 kg of soil was put into a pot, and then an agave propagule was transplanted into each pot. The soil surface was covered with small styrene foam granules to minimize evaporation. The agave propagules examined were *Agave vilmoriniana*, *A. americana*, and *A. weberi* (Fig. 11). The experiment was a completely randomized design (Gomez and Gomez, 1984): 6 treatments and 4 replicates. Pots were arranged lengthways with 2 rows and rotated randomly once every two weeks (Fig. 12). The same amount of tap water was supplied to both soil types, whose field capacity is 10.7 % for gravelly sandy loam and 38.2 % for clay loam. The amount of tap water which was adequate to not cause water stress on agave growth, was supplied to pots once every two weeks, and the amount of water was 300 cc for *A. vilmoriniana* and *A. americana*, 500 cc for *A. weberi*. The propagules of *A. weberi* was much bigger than the other two, so more water was supplied to *A. weberi*. There was no fertilizer application. In January 24, 1992, fresh weights, leaf lengths and number of expanded leaves agave propagules were measured and counted.

Statistical Analysis

Statistical methods were applied to evaluate the relationships between soil type and agave growth in the greenhouse experiment. The parameters which were used for the analysis were number of expanded leaves, leaf length, fresh weights, and dry matter weight. All analyses were carried out using the Statistical Analysis System (SAS) package (SAS, 1984).

Fig. 11. Seedlings of agaves examined.

Fig. 12. Pot arrangement in the greenhouse experiment.

4. RESULTS

Soil Characteristics of Study Sites

All Soils from Texas Canyon contain a large quantity of coarse fragments and have high sand content with a low content of clay and a high content of organic matter in comparison to the other soils (Table 8 and 9). The coarse fragment content of Texas Canyon soils ranges from 32 % to 42 % and include four soil textured classes, which are gravelly sandy clay loam, very gravelly sandy clay loam, gravelly sandy loam, and very gravelly sandy loam. The soils from Marana and Safford sites are rich in clay, whose content in the 0-25 cm depth is 35.3 % in the Marana soil and 38.7 % in the Safford soil. Both soil texture classes are clay loam. The Avra Valley soils contain a high percentage of sand, which is 64.6 % in the 0-25 cm depth, and their texture class is sandy loam. The Page Ranch soils contain relatively high amounts of clay compared with the Avra Valley soils, and the clay content of the Page Ranch soils is 21.6 % in the 0-10 cm and 34.0 % in the 10-25 cm depth. The Marana, Avra Valley, and Safford soils contain relatively high amounts of fine sand, but in contrast coarse sand dominates in the Page Ranch and Texas Canyon soils (Table 8).

The Texas Canyon, Triangle T Ranch, Salt Spot soil is not a representative soil sample in the context of the relationship between agave growth and soil properties, but was analyzed in order to evaluate the state of the salt accumulation in the low spot and for the reference for later discussion. Therefore, this soil sample is excluded from this section. The moisture retention level at -1.5 MPa increases with increasing clay content (Table 8). The highest moisture content of 16.2 % was recorded in the Safford soils in

Table 8. Soil texture, sand fractionated and moisture content at -1.5 MPa of soil samples from study sites.

Depth (cm)	Coarse frag. (%)	Total sand (%)	Total silt (%)	Total clay (%)	Sand fractionated 2.0-1.0 mm (%)	1.0-0.5 mm (%)	0.5-0.25 mm (%)	0.25-0.1 mm (%)	0.1-0.05 mm (%)	Textured class	Moisture at -1.5 MPa (%)
Marana											
0-25	0	28.9	35.8	35.3	1.2	1.8	1.7	9.0	15.2	Clay loam	14.6
25-50	0	23.0	40.2	36.8	0.6	1.1	1.1	6.8	13.4	Clay loam	14.9
Avra Valley											
0-25	0	64.6	19.6	15.8	1.9	6.3	8.5	25.4	22.5	Sandy loam	5.7
25-50	0	62.0	22.6	15.4	2.5	6.0	8.2	22.2	23.1	Sandy loam	5.9
Page Ranch											
0-10	0.9	62.8	15.6	21.6	24.0	14.9	6.5	5.9	11.5	Sandy clay loam	4.5
10-25	1.0	46.0	20.0	34.0	17.7	12.2	5.2	4.2	6.7	Sandy clay loam	12.2
Texas Canyon, Walnut Wash, North Saddle											
0-10	42.0	71.4	12.8	15.8	15.0	17.5	10.7	17.5	10.7	Very Gravelly sandy clay loam	6.6
10-25	31.8	55.6	13.6	30.8	19.2	16.7	6.4	7.0	6.3	Gravelly sandy clay loam	13.1
Texas Canyon, Walnut Wash, South Saddle											
0-10	33.5	75.0	8.5	16.5	19.4	22.0	10.7	14.2	8.7	Gravelly sandy loam	6.4
10-25	39.8	56.6	12.9	30.5	18.2	17.2	6.5	6.6	8.1	Very gravelly sandy clay loam	12.7
Texas Canyon, Adams Peak, North											
Surface	32.5	74.0	11.7	14.3	17.7	18.1	9.9	17.5	10.8	Gravelly sandy loam	5.8
Texas Canyon, Adams Peak, South											
Surface	34.4	73.4	14.8	11.8	21.9	17.3	8.3	15.3	10.6	Gravelly sandy loam	5.3
Texas Canyon, Triangle T Ranch											
Surface	39.2	76.7	9.2	14.1	20.8	20.7	9.8	15.2	10.2	Very gravelly sandy loam	5.0
Texas Canyon, Triangle T Ranch, Salt Spot											
Surface	14.0	79.6	5.9	14.5	18.8	22.4	10.1	17.4	10.9	Sandy loam	2.8
Safford											
0-25	0	29.6	31.7	38.7	0.6	1.5	2.6	15.0	9.9	Clay loam	16.2
25-50	0	27.5	35.8	36.7	0.5	1.5	2.4	14.4	8.7	Clay loam	17.0

which the top soil contains 38.7% of clay. The Texas Canyon soil is low in clay, and exhibited low moisture content at -1.5 MPa. The Texas Canyon, Triangle T, Ranch soil recorded the lowest moisture retention, 5.0%, at -1.5 MPa.

The pH values of the Texas Canyon soils range from 5.36 to 6.19, which is moderately to slightly acid (Table 9). The top soil of Page Ranch showed the lowest pH value, 5.18. The Marana and Avra Valley soils are slightly alkaline, and the pH values of the top soils are 7.75 and 7.70, respectively. The Safford soil recorded the highest pH value, 8.22 in the 0-25 cm and 8.13 in the 25-50 cm depth.

The salinity levels of most soil samples are low except for the Safford soils (Table 9). The EC values of the Safford soils are 2.28 dS m^{-1} in the 0-25 cm depth and 3.01 dS m^{-1} in the 25-50 cm depth, but other soils showed less than 1 dS m^{-1}. The Safford soils also exhibited high SAR, whose value were 21.0 in the 0-25 cm and 22.4 in the 25-50 cm depth. The SAR of the other soils are less than 2.5.

The Page Ranch soils contain the lowest Ca, Mg, Na, and K, with values of 16.0, 2.71, 15.8, and 9.99 ppm, respectively (Table 9). The amount of Ca in the Maran0a and Avra Valley soils is relatively high with 76.4 ppm in the top soil of Marana and 74.0 ppm in the top soil of Avra Valley. The Safford soils are quite high in Na, with a value of 515 ppm in the 0-25 cm and 678 ppm in the 25-50 cm depth.

Field Observations and Biomass Accumulation

All data cited in this section are from McDaniel (1985, personal communication, 1992). Table 10 shows the growth condition of agave species in four study sites. Each

Table 9. pH, EC, Ca, Mg, Na, K, SAR, and OC of soil samples from study sites.

Depth (cm)	pH	EC (dS m^{-1})	Ca (ppm)	Mg (ppm)	Na (ppm)	K (ppm)	OC (OM) (%)	SAR
Marana								
0-25	7.75	0.62	76.4	5.68	56.7	30.2	0.53 (1.30)	1.69
25-50	7.69	0.52	55.0	4.28	59.8	16.8	0.32 (0.93)	2.09
Avra Valley								
0-25	7.70	0.60	74.0	8.60	47.9	26.8	0.21 (0.73)	1.40
25-50	7.70	0.96	100	12.1	100	17.5	0.11 (0.55)	2.51
Page Ranch								
0-10	5.18	0.19	16.0	2.71	15.8	9.99	0.48 (1.21)	0.96
10-25	6.22	0.32	23.4	5.64	42.7	3.41	0.52 (1.29)	2.06
Texas Canyon, Walnut Wash, North Saddle								
0-10	5.92	0.33	33.3	7.19	23.1	13.9	1.30 (2.69)	0.95
10-25	6.19	0.51	57.2	14.7	36.3	12.0	1.19 (2.49)	1.11
Texas Canyon, Walnut Wash, South Saddle								
0-10	6.16	0.34	51.9	8.41	33.0	15.1	1.16 (2.44)	1.12
10-25	6.13	0.39	52.2	8.47	26.6	5.82	1.00 (2.15)	0.90
Texas Canyon, Adams Peak, North								
Surface	5.83	0.63	67.2	11.4	46.1	15.6	1.16 (2.44)	1.37
Texas Canyon, Adams Peak, South								
Surface	5.36	1.13	111	23.5	91.7	14.2	1.08 (2.29)	2.06
Texas Canyon, Triangle T Ranch								
Surface	5.50	0.27	35.0	4.61	24.0	5.99	0.97 (2.10)	1.01
Texas Canyon, Triangle T Ranch (salt spot)								
Surface	7.86	4.97	45.8	5.14	1280	28.5	0.35 (0.98)	47.8
Safford								
0-25	8.22	2.28	39.1	3.87	515	10.6	0.61 (1.45)	21.0
25-50	8.13	3.01	58.3	6.66	678	12.3	0.63 (1.48)	22.4

agave species responded to different environmental conditions in a different manner, and the pattern of the responses of agaves was different among different species. *Agave Americana* grew relatively well in four fields, but the environmental conditions of

Table 10. Agave species evaluated under cultivation.

Field location	Species	Evaluation
Marana	*Agave americana*	Rapid growth, well adapted, many off-shoots
	A. deserti	Slow growth
	A. foucroydes	Failed to survive winter because of low air temperature
	A. murpheyi	Rapid growth, prone to waterlogging
	A. palmeri	Slow growth
	A. parryi	Extremely slow growth
	A. sisalana	Rapid growth
	A. vilmoriniana	Rapid growth, well adapted
	A. weberi	Rapid growth, well adapted
Avra Valley	*A. americana*	Rapid growth
	A. murpheyi	Medium growth because of agave weevils
	A. palmeri	Slow growth
Page Ranch	*A. americana*	Rapid growth, few off-shoots
	A. palmeri	Slow growth, some mortality
	A. murpheyi	Slow growth, high mortality because of low air temperature
Safford	*A. americana*	Rapid growth, some off-shoots
	A. palmeri	Slow growth, high mortality at high salinity level

Marana seemed to be the best for *A. americana*. Biomass accumulation of *A. americana* was particularly high in the Marana field in comparison to the Avra Valley, Safford, and Page Ranch fields (Fig. 13).

The growth of *A. murpheyi* slowed down and frequently ceased in the Page Ranch field with low air temperature and in the Safford field with high salinity. In the Avra Valley field, *A. murpheyi* was severely attacked by agave weevils. Agave weevil attacks were observed in *A. americana*, *A. sisalana*, and *A. murpheyi* in the Marana field and *A. americana* in the Page Ranch field.

A. palmeri exhibited low growth in the Marana, Page Ranch, and Safford fields, especially in the Safford saline soil. In the Marana field, the growth of *A. parryi* was extremely slow, and *A. foucroydes* died during the winter, but in the meantime *A. murpheyi*, *A. sisalana*, *A. vilmoriniana*, and *A. weberi* appeared to be well adapted to the Marana environment, just as was *A. americana* (Fig. 13). The growth rate of *A. deserti* in the Marana field was slow in comparison to the well-adapted species (Fig. 14).

The three serial pictures of Figure 15 show the growth responses of *A. americana* and *A. palmeri* at three levels of salinity in irrigation water (ECw) in the Safford field. The growth of both species appears to be limited even in the lowest ECw, 0.85 mmho cm^{-1}, which is a match for soil salinity (ECe) level of 1.28 mmho cm^{-1}. In the highest ECw plot, severe growth retardation was observed in *A. palmeri*. Figure 16 shows the relative tolerance of *A. americana* and *A. palmeri* to salinity in the Safford field. Since the rate of biomass decrease of *A. americana* was slower than that of *A. palmeri*, *A. americana* appears to have more tolerance to salinity than *A. palmeri*.

Figure 17 shows the biomass accumulation of *A. vilmoriniana*, which was blooming 6 years after its bulbil was transplanted.

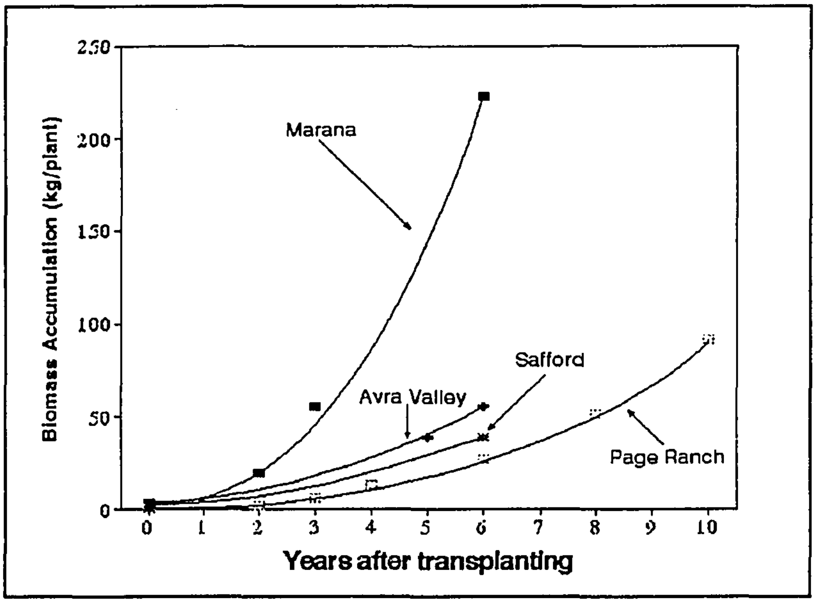

Fig. 13. Relative biomass accumulation of *Agave americana* cultivated at four study sites.

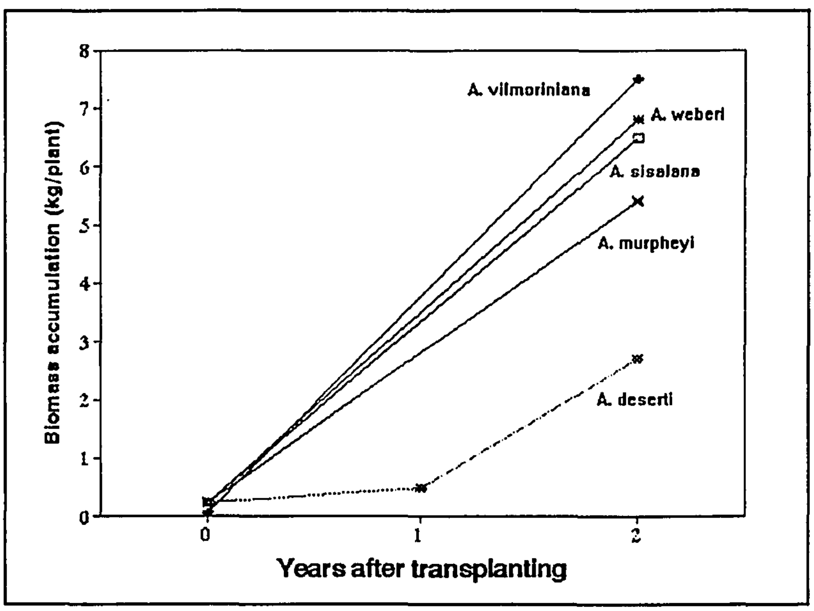

Fig 14. Biomass accumulation of five agave species in the Marana field.

a)

b)

c)

Fig. 15. Growth responses of *Agave americana* and *A. palmeri* at three different levels of salinity: a) $EC_w = 0.85$ dS m^{-1} ($ECe = 1.28$ dS m^{-1}), b) $EC_w = 1.09$ dS m^{-1} ($ECe = 1.64$ dS m^{-1}), and c) $EC_w = 2.33$ dS m^{-1} ($ECe = 3.50$ dS m^{-1}). The conversion of ECw to ECe was carried out using the following formula: ECe = 1.5 ECw (Ayers and Westcot, 1989)

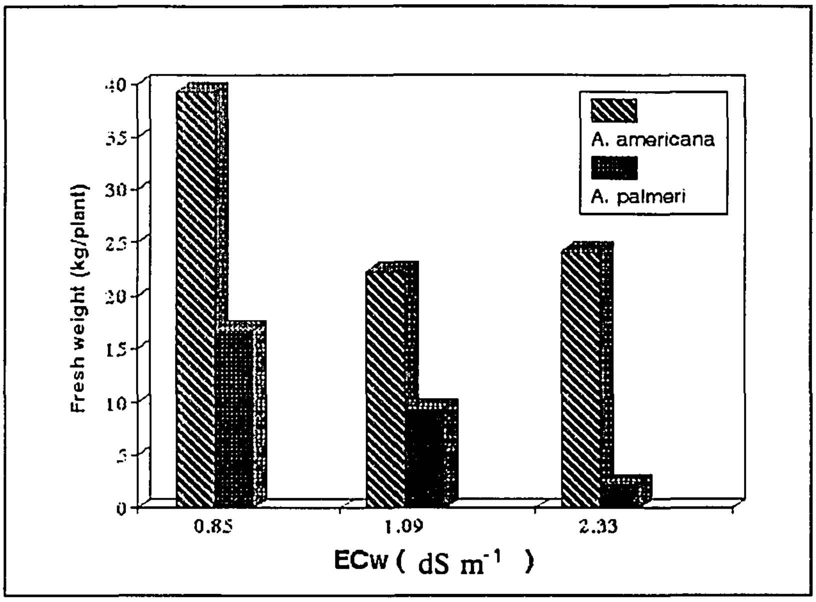

Fig. 16. Fresh weight of two agave species at three levels of ECw in the Safford field.

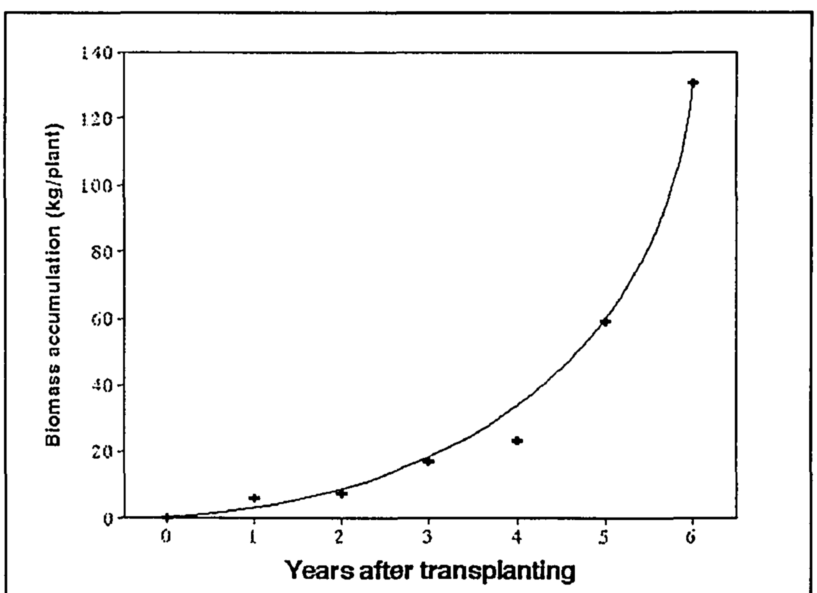

Fig. 17. Biomass accumulation of *Agave vilmoriniana* in the Marana field.

Climatic Conditions

Mean annual air temperatures in January and July, mean annual precipitation, mean greatest precipitation per one day in July, and mean cumulative snow & sleet from November to March were calculated and cited from each climatic data source for each study site (Table 11). Page Ranch, Texas Canyon, and Safford areas were relatively cooler than Marana and Avra Vally areas. The highest mean annual air temperatures in January and July, 4.5 and 38.5 °C, were recorded at the Marana Agricultural Center. The lowest records in January and July were -3.6 °C in Willcox and 32.8 in Oracle 2 SE,

Table 11. Mean annual air temperature, mean annual precipitation, mean greatest precipitation per one day, and mean cumulative snow & sleet in study sites.

Study site (Observatory)	Mean annual air temperature (°C) Jan.	Jul.	Mean annual precipitation (mm)	Mean greatest precipitation per one day in July (mm)	Mean cumulative snow & sleet from November to March (mm)
Marana (Marana agricultural center)[a]	4.5	38.5	262	no data	no data
Avra Valley (Arizona Sonora Desert Musium)[b]	4.2	38.0	244	61	Trace
Page Ranch (Oracle 2 SE)[c]	1.6	32.8	437	73	574
Texas Canyon (Willcox)[c]	-3.6	34.6	254	30	104
Safford (Safford Agricultural Center)[c]	-2.7	36.2	224	14	57

[a] Data from Nobel and McDaniel (1988)

[b] Data from Arizona Climate (1974)

[c] Data from NOAA (1986-1990)

respectively. The Page Ranch area had the highest mean annual precipitation, 437 mm, among the five study sites. The mean annual precipitation of the other four sites were around 250 mm, and the lowest precipitation, 224 mm, was recorded at the Safford Agricultural Center. The snowfall and sleet frequently occured in the Page Ranch area during the winter.

Greenhouse Experiment

Table 12 presents 4 variables which were investigated at harvest, and there was slight difference in the growth of agave species between clay loam and graverlly sandy loam. There was no significant difference at 5% level between the final number of expanded leaves and leaf length in clay loam and those in gravelly sandy loam (Table 14). The fresh weight and dry matter weight of *A. weberi* and *A. americana* did not show any significant difference at 5% level in the both soils, but on the other hand *A. vilmoriniana* exhibited a significant difference at 5% level in the fresh weight and at 1% level in the dry matter weight (Table 15). Under the controlled condition, *A. vilmoriniana* grew well in the clay loam soil, but not in the gravelly sandy loam soil. And *A. weberi* and *A. americana* equally grew in the both soil types.

Table 12. Mean final # of expanded leaves, leaf length, fresh weight, and dry matter weight in the greenhouse experiment.

Treatment	Mean final # of expanded (cm)	Mean final leaf length (g)	Mean final fresh weight (g)	Mean final dry matter weight (g)
Clay loam + *Agave vilmoriniana*	4.3	27.8	180	22.9
Gravelly sandy loam + *A. vilmoriniana*	3.5	24.3	147	17.5
Clay loam + *A. americana*	2.8	13.5	114	12.2
Gravelly sandy loam + *A. americana*	2.5	13.3	147	15.1
Clay loam + *A. weberi*	0.8	35.5	1467	383
Gravelly sandy loam + *A. weberi*	1.8	34.3	1426	377

Table 13. Summary of observed F values for final leaf length and final # of expanded leaves of three transplanted agave species.

Factor (Trait measured)	F value	Significance (5%)
Final leaf length of *Agave vilmoriniana*	2.75	not significant
Final leaf length of *A. americana*	0.10	not significant
Final leaf length of *A. weberi*	1.47	not significant
Final # of expanded leaves of *A. vilmoriniana*	3.43	not significant
Final # of expanded leaves of *A. americana*	2.00	not significant
Final # of expanded leaves of *A. weberi*	2.42	not significant

Table 14. Summary of observed F values for biomass accumulation of three transplanted agave species.

Biomass accumulation (fresh weig t in gram)

A. vilmoriniana

Source	Degree of freedom (DF)	Mean square (MS)	F value
Model	1	2178	8.77*
Error	6	248	

A. americana

Source	DF	MS	F value
Model	1	2145	1.53
Error	6	1403	

A. weberi

Source	DF	MS	F value
Model	1	3403	0.07
Error	6	51339	

Biomass accumulation (dry matter weight in gram)

A. vilmoriniana

Source	DF	MS	F value
Model	1	61	12.52**
Error	6	5	

A. americana

Source	DF	MS	F value
Model	1	21	1.17
Error	6	18	

A. weberi

Source	DF	MS	F value
Model	1	66	0.02
Error	6	3192	

* Denotes significance at the 5% level
** Denotes significance at the 1% level

5. DISCUSSION

Determinant Factors for the Productivity of Agaves

There was an evident difference in the productivity of *Agave americana* among the four study sites, Marana, Avra Valley, Page Ranch, and Safford (Fig. 13). By comparing the effect of climatic conditions and soil properties of the four sites and considering the results of previous studies, factors for the productivity of agaves and relative favorable soil conditions for agave growth were determined. Previous studies suggest that soil water availability, soil CO_2 concentration in the root zone, soil temperature, N content, Ca content, Na content, and soil pH are major influential soil factors on agave growth. When these soil factors are standards against which the results of field and greenhouse experiments are compared, several hypotheses to explain the productivity of *A. americana* in the four sites are possible.

In the Marana field, there are six possible reasons for high productivity. Weather during the winter is relatively warm (4.5 °C in January) in comparison to the other three sites. Rainfall (262 mm) plus one or two supplemental irrigations per year (approximately 90 mm each apprication) would provide sufficient water for healthy growth even in the clay loam soil. Soil CO_2 levels might not be so high for *A. americana* in the Marana clay loam soil. The soil is relatively fertile, that is, the soil is high in N (0.1 %) and Ca (76.4 ppm) and low in Na (56.7 ppm). Soil pH level (7.75) is close to the optimum level.

The major cause of the low productivity of *A. americana* in the Avra Valley, Safford, and Page Ranch fields could be due to unfavorable climatic and entomological conditions for agave growth. Annual precipitation in the Avra Valley area is about 250 mm, and this amount of water is not enough to support healthy growth. The severe attack by agave weevils was also observed in the Avra Valley field. Air temperature (-2.7 °C in January) is relatively low during the winter at the elevation of the Safford field. Frost frequently occurs during the winter at the elevation of the Page Ranch field (1146 mm).

In terms of soil conditions, the Avra Valley soil may contain relatively low N because organic matter is the lowest, 0.7 %, of all soil samples (Table 9). The soil of the Page Ranch field is low in N (0.06 %), Ca (16 ppm), and pH (5.18 in the 0-10 cm depth and 6.22 in the 10-25 cm depth). The Safford soil is relatively low in Ca (39.1 %) and high in Na (515 ppm) and pH (8.22). The CO_2 levels in the root zone of the Safford soil may be high because of poor aeration due to deflocculation of clay particles caused by high Na ion concentration

Effects of Soil Texture on Agave Growth

Water Availability

Agave species generally grow well in well-aerated and drained soils such as sandy soils (Cannon, 1911; Gentry, 1982; Nobel, 1988). The results of this research proved that five species of agaves, *Agave americana*, *A. murpheyi*, *A. weberi*, *A. vilmoriniana*, and *A. sisalana* can also grow well in the clay loam soil of the Marana site (Fig. 13 and 14). *A. deserti* which exhibited slow growth in the Marana clay loam soil, is originally a slow growing species in the agave family, and its growth rate in Marana nearly equals that in its natural habitat which is desert with sandy soils (Fig. 13) (McDaniel, personal communication, 1992). The productivity of *A. americana* in the Marana clay loam soil was much higher than those in the other three fields (Fig. 13).

The major advantage of sandy soils with coarse fragments for plants in arid zones is high water availability due to deep water penetration in comparison to clayey soils (Hillel and Tadmor, 1962; Noy-Meir, 1973; Walter and Stadelman, 1974; Nobel, 1988). The behavior of the five agave species seems to be opposite to the previous reports in terms of the effect of soil texture on water retention.

Soil texture is the primary factor which controls soil water retention, soil aeration, and nutrient content. One possible explanation of the healthy growth of agaves in clayey soil can be the supplemental irrigation of the Marana clay loam soil which generally provides low water availability to plants in natural arid habitats. The mean annual precipitation in the Marana area is about 262 mm (Table 11). This amount of precipitation is considered marginal for healthy growth, so minimal irrigation was carried out to raise total precipitation level up to the level of the Page Ranch area, which is 437 mm (Table 11). Approximately 90 mm of supplemental irrigation was carried out once or twice per year in the Marana field (McDaniel, personal communication, 1992). The total porosity of the Marana clay loam soil is 44.6% in the Ap horizon of the Pima I site of Marana Agricultural Center and 46.8% in the Ap horizon of the Pima II site (Post et al., 1978). The calculated depth of water penetration using the average porosity 45.7% is about 20 cm. This depth is enough to reach the shallow root zone of agaves. Thus, these five species of well-grown agaves could store sufficient water for their growth with supplemental irrigations.

Daily precipitation in arid regions never reaches 90 mm. Even the greatest precipitation per day in the Page Ranch area is 73 mm, and that in Willcox is only 30 mm, which will be little higher in the Texas Canyon sites because the elevation of Texas Canyon is higher than Willcox (Table 11). However, a small amount of precipitation per day to porous sandy soils containing gravel or rock fragments is the most effective water supply system for natural desert plants to survive in arid regions. This may explain why natural habitats of agaves are usually stony and rocky mountain slopes, such as Texas Canyon (Table 2 and Fig. 6-8). Slopes also contribute runon of rainwater from upslope to agaves during a heavy rainfall. The rockpile field for agave cultivation by pre-Columbian native Americans on mountain slopes of southern Arizona is a highly efficient method of cultivation using only rainwater.

If a large amount of precipitation falls on the clayey soil within a short period, even the clayey soil can provide enough water for plants in arid regions. Although clayey soils have low hydraulic conductivity due to high water retention and small pore size, water can penetrate deep enough to reach the root zone and is absorbeb by plants before it evaporates. From a standpoint of water availability to agaves, the importance of soil texture depends upon water quantity supplied. That is, if a necessary amount of water for healthy growth is supplied to agaves, soil texture is not an important factor determine water availability to plants. When the amount of water is, however, limited, soil texture is a crucial factor to determine water availability to agaves. The work of Le Houerou (1983) supports this hypothesis in terms of the water limited situation. He found that the productivity of olive trees in Tunisia is higher on sandy soils when mean rainfall is less than 300 mm compared with silty and loamy soils. But silty and loamy soils exhibits higher productivity than sandy soils when mean rainfall reaches more than 450 mm.

The results of greenhouse experiments also support the hypothesis. Under well-watered conditions, *A. americana* and *A. weberi* did not show any significant difference in their growth between the clay loam soil and gravelly sandy loam (Table 13 and 14). The significant difference in the fresh and dry weight of *A. vilmoriniana* is related to nutrient levels of soils examined (Table 14). This is discussed in the nutrient section later in this chapter.

CO_2 Concentration in the Soil

Agave parryi and *A. palmeri* exhibited slow growth in the Marana clay loam soil (Table 10). The cause of slow growth may be due to factors other than water availability since water availability in the Marana field was equal for every species. One probable cause of the slow growth may be the increase of CO_2 concentration due to poor soil aeration and high air temperature.

Agaves tend to be sensitive to high soil CO_2 concentration (Nobel, 1990a), and the mean air temperature of July of natural habitats of *A. parryi* and *A. palmeri* is lower than that of the Marana area (Table 1). However, two species exhibit high temperature tolerance: *A. parryi* loses 50% of cell activity at the temperature range from 59.5 °C to 61.3 °C, and the 50% inhibition of cell activity occurs in A. palmeri when the temperature is between 61.3 °C and 62.5 °C (Nobel and Smith, 1983).

High air temperature appears not to be a cause of slow growth. The soil CO_2 concentration of the Marana clay loam soil might then be the major cause in the slow growth of the two species. During the summer, whenever there is an occasional rain, microbial activity will be promoted in the wet and warm soils. Moreover, the Marana clay loam soil provides the optimum soil pH range and relatively high nutrients for the growth of microorganisms (Table 9). Microbial activaty leads to consumption of O_2 and production of CO_2 in the soil. Especially, microbial activity is more vigorous around the rhizosphere because of root exudates (Paul and Clark, 1989). The aeration of clayey soils is inherently poor owing to small pore size (Singer and Munns, 1987). For these reasons, the CO_2 concentration of the Marana clay loam soil may be relatively high in comparison to soils of other study sites.

The sensitivity to soil CO_2, however, largely depends upon the biological characteristics of each agave species. The two species which exhibited slow growth were sensitive to the soil CO_2 level in the Marana clay loam soil. But on the other hand the soil CO2 level does not appreciably affect the growth of *A. americana*, *A. weberi*, *A. murpheyi*, *A. vilmoriniana*, and *A. sisalana*.

Effect of N and Ca on Agave Growth

The second soil factor which led tothe high productivity of *Agave americana* in the Marana field may be the high soil N content. The soil N was 0.1% in the Marana soil and 0.06% in the Page Ranch soil (Nobel, 1989). According to Nobel (1989), the minimum night time air temperature in both sites was at a level that would not affect the nocturnal CO_2 uptake of agaves. Under relatively similar climatic conditions, nutrient levels of the soil must be a determinant factor for plant productivity. N is a vitally important nutrient for all plants (Tisdale et al., 1985). Nobel (1989) reported that the growth of *A. deserti* was much greater in the Marana field than in the Page Ranch field.

There is no available data about N levels in the Avra Valley and Safford field. If a rough estimation is carried out from the land situation of the two sites, the Avra Valley site will be low in N since it occurs in an abandoned cotton field with sandy loam soil, and the Safford soil will contain relatively high N because it is in a cultivated land with a clay loam texture. However, the major causes of low productivity of *A. americana* in the Safford and Avra Valley fields is the unfavorable climatic and entomological conditions. Therefore, biomass data of these two fields will not be suitable for the discussion of the effect of N.

The key factor of agave growth in the greenhouse experiment appears to be the N content in the soil examined. *A. vilmoriniana* is the fastest growing species among the three agave species examined in the greenhouse experiment, so the response of the species to N may be the most rapid of these three agave species. Since the Marana field is cultivated land, and the pH value of the Texas Canyon Triangle T Ranch soil is 5.50, the N content and availability of the Marana soil was presumably higher than that of the Texas Canyon Triangle T Ranch soil. In fact, the shade of the leaf color of *A. vilmoriniana* which was grown in the Marana soil was darker than that of the species in the Texas Canyon Triangle T Ranch soil during the greenhouse experiment (Author's observation, 1992). Accordingly, if the greenhouse growth experiment had continued several more months, *A. americana* and *A. weberi* which are relatively slow growing species compared with *A. vilmoriniana* would be expected to have exhibited better growth in the Marana soil.

The effect of soil Ca content on agave growth will be related to the availability of P to agaves. Lock (1969) reported that the input of a large amount of Ca into acidic soils improved the yield of *A. sisalana*. This could be due to the release of P from Al and Fe compounds in acidic soils by the increase of soil pH caused by the imput of Ca. Nobel and his colleagues (1988) proved that A. deserti responded well to the increase of soil P levels. Hence, the significance of Ca existence in the soil for agave growth may not be as an essential nutrient, but as an important element for the release of P in acidic soils. The statement of Nobel and Berry (1984) that agaves are insensitive to Ca because they occur in soils with a wide range of Ca content will be correct in normal soils, but in acidic soils agaves will be sensitive to Ca. The Nobel's NI index (1989) should be also discussed in terms of the effect of the soil pH on nutrient availability. The Ca content is much higher in the soils at the Marana site than at the Page Ranch and Texas Canyon Triangle T Ranch sites (Table 9). This also might contribute to the availability of P in the Marana soil for the growth of agaves.

Effect of Na on Agave Growth

The growth retardation of *Agave americana* and *A. palmeri* in the Safford field with increasing ECw could be caused by high Na content in the irrigation water. The soil sample from the field adjacent to the experiment field contains 515 ppm Na, and its EC value was 2.28 dS m^{-1} and SAR was 21.0 (Table 9). Agaves can grow in soils whose EC values are extremely high, but these high soil EC levels were caused by high Ca concentration (Table 4). Even the highest ECw in the experiment, 2.33 dS m^{-1} which is a match for soil EC, 3.50 dS m^{-1}, is not categorized as saline water or soils by U.S. Salinity Laboratory Staff (1954), whose standard about saline soils is that EC is more than 4 dS m^{-1}. From these facts, the following hypotheses are formulated; 1) three different EC levels of irrigation water which were used for the experiment will be higher in Na than in other soluble salts, 2) the SAR value in the irrigation water of the Safford field will be high, and 3) Saline soils caused by high Ca will not damage agaves, but saline soils high in Na and sodic soils will cause serious retardation of agave growth.

There is no natural population of agaves in the bottom of the mountain valleys of Texas Canyon. This may be due to salt accumulation, and especially high Na concentration. The soil from the Texas Canyon Triangle T Ranch salt spot located at the bottom of a hill contained 1280 ppm Na (Table 9). This Na value represents an extreme example, but the soils of the bottom area of hills in Texas Canyon will contain relatively high amount of Na compared with the area where *A. palmeri* occurs. Low temperatures due in part to cold air drainage to the bottom area may also be a possible reason to explain the absence of a natural population of *A. palmeri* (McDaniel, personal communication, 1992).

Effects of Soil pH on Agave Growth

The soil pH is also an important factor on the availability of many nutrients to plants. In this research, determinant factors for the productivity of agaves in the study sites which have soils low in pH were unfavorable climatic conditions. Hence, the effect of soil pH on agave growth are not clearly described.

Since soil pH is definitely an important factor related to nutrient availability to plants, the following hypotheses may be at least suggested. The Page Ranch soil has the lowest pH (5.18) of all soil samples at the 0-10 cm depth (Table 9). This pH value is lower than the optimum pH range for nitrification, which is between pH 6 and 8 (Paul and Clark, 1989). This low soil pH may also be one of causes of low productivity of *Agave americana* in the Page Ranch field. In contrast, the soil pH of the Marana field is weakly alkaline (pH 7.75). This pH value is still in the optimum pH range for the microbial growth.

Feasibility of Agave Culture in Arizona

The results of experimental cultivations by McDaniel (1985, unpublished data, 1992) proved that several species of agaves which are not native to Arizona adapted well to southern Arizona and exhibited high productivity indicating that agave cultivation is feasible. The environmental conditions in the Marana field seem to be relatively favorable for most species examined. Fields for agave culture should be selected in terms of the following environmental factors; annual precipitation, air temperature during the winter, and soil texture. For agave cultivation in southern Arizona, clayey or loamy soils may exhibit high productivity with minimal supplemental irrigations.

Further investigations to determine the best environmental conditions for each valuable species is still necessary for the establishment of effective agave cultivation systems. The demand for agave products must also be surveyed before agave culture is started. Agave culture in southern Arizona should be considered from a standpoint of multiple use (McDaniel, 1985).

One high potential agave species for commercial cultivation in southern Arizona will be *Agave vilmoriniana*. The species contains 0.5-4.4% of sapogenins in its leaves, and that content is the highest in the agave family (Gentry, 1982). The major advantages of this species are that the market value per product is much higher than other agave products, such as sisal fiber and tequila, and the mechanized harvest is possible (Gentry, 1982). This species grew well in the Marana field (Fig. 16). At the blooming stage 6 years after the bulbil of the species was transplanted, the fresh weight of the species reached 130.4 kg $plant^{-1}$ (McDaniel, unpublished data, 1992).

The major probable problem in agave cultivation could be the control of agave weevils (McDaniel, personal communication, 1992). Control methods of agave weevils must be also studied. The control technique should include fewer chemicals and less labor to achieve the primary objective of the introduction of agave cultivation in southern Arizona.

6. CONCLUSION

The successful growth experiment of several agave species in the Marana clay loam soil is mainly due to favorable water status caused by one or two supplemental minimal irrigations per year. For sandy soil, supplemental irrigations will be ineffective and wasteful for agave which has shallow root systems because water will permeate deep and drain fast. In arid regions whose annual precipitation is less than 250 mm, supplemental irrigation will be more efficient in clayey soil than in sandy soil for agave cultivation.

Under favorable climatic conditions, soil properties play a determinant role on agave growth. Soil texture will be the most important factor of all soil properties affecting agave growth in arid regions from a standpoint of water availability when the water supply is restricted. Soil CO_2 concentration in the root zone may influence the growth of agaves. N will be the key nutrient for the high productivity of agaves. Ca will be an important element to increase soil pH of acidic soil and release available P to agaves. Soil pH is an important factor in the context of N and P availability to agaves. High soil EC due to high Ca content does not cause any growth retardation, but high soil EC due to high Na content adversely affects agave growth rates.

The extent of water requirement, tolerance to CO_2, N and P requirement, and tolerance to Na depend upon the genetic characteristics of each agave species. Several of the agave species evaluated can be distinguished by differences in their growth response to various environmental conditions.

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