Pre-Columbian Rock Mulching as a Strategy for Modern *Agave* Cultivation in Arid Marginal Lands

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Cultivation of C_3 and C_4 crops in semi-arid regions will be severely constrained as global temperatures rise. Consequently, alternative crops need to be sought out that adapt well to heat and drought and are productive despite limited access to water. Traits, such as crassulacean acid metabolism (CAM), enable economically important species such as those in the *Agave* genus adapt to drought and high temperatures. The succulence and high efficiency of agaves, which enables them to produce biomass with little water, underscores their feasibility as an alternative crop for semi-arid regions, such as the Sonoran Desert in the southwestern U.S. In this paper, we offer a review of the suitability for cultivation of agaves *via* dryland farming, particularly by rock mulching techniques used by pre-Columbian, Sonoran Desert farmers. This analysis dovetails with information also provided on the biological traits of *Agave* and its historical and present utilization. Pre-Columbian, Hohokam dryland farmers used rock mulching in the form of rock piles to cultivate agaves. Rock piles acted as a type of mulch to harvest rainfall and to retain soil moisture, which allowed the Hohokam to intensively cultivate agaves during multi-year droughts. Remains of Hohokam rock mulching for agave production can be found at archaeological sites in central Arizona, which provides evidence of the utility of dryland farming and ancient agricultural innovation to reconcile water scarcity in the region. Moreover, the use of rock piles likely bolstered *Agave* productivity in marginal lands. Although little is known of historic rock mulching to cultivate agaves and its biological implications on plant productivity we suggest its application as a dryland farming model could be a sustainable strategy in the U.S. Southwest.

Keywords: crassulacean, succulent, dryland farming, rock mulching, rock piles

INTRODUCTION

Increasingly limited access to water and elevating temperatures will continue to hamper productivity of conventional C_3 and C_4 crops in arid and semi-arid regions throughout the world in the coming decades (Porter and Semenov, 2005; De Micco and Aronne, 2012; Zandalinas et al., 2018). Contemporary agricultural challenges, limited water availability, and rising temperatures have constrained agriculture in dry regions throughout history (Ingram, 2010). Within the last 1,300 years, global warming has been associated with overexploitation of natural resources, increased urbanization, and accelerated agricultural development (Woodhouse et al., 2010). Models of changes in global temperature suggest that induced anthropogenic global warming became more frequent during the Medieval Warm Period, which occurred between 700 and 1300 CE (Galloway, 1986; Hughes and Diaz, 1994; Bradley et al., 2003; Stinchcomb et al., 2011). The Medieval Warm Period increased temperatures and reduced water levels of lakes and rivers throughout Europe, Asia, and North and South America (Van West and Dean, 2000; Chu et al., 2002; Sridhar et al., 2006; Helama et al., 2009; Woodhouse et al., 2010). In addition to the Medieval Warm Period, some have hypothesized that global temperatures rose and rainfall patterns progressively changed in arid regions during the pre-industrial period 800–1850 A.D. due to land-use changes for agriculture (e.g., conversion of forests and grasslands into cropland) (Galloway, 1986; Reick et al., 2010; Pongratz and Caldeira, 2012).

After the Industrial Revolution, the use of fossil fuels and concomitant increases in CO_2 emissions accelerated climate change (Callendar, 1938; Revelle and Suess, 1957; Neftel et al., 1985; Lemonnier and Ainsworth, 2018), increasing global temperatures and the occurrence of droughts during the twentieth century (Hansen et al., 1981; Solomon et al., 2010; Smith et al., 2019). At the end of the last century and beginning of the twenty-first century, globalized industrial development and creation of large urban centers resulted in cropland expansion in arid and semi-arid regions to meet increased food-production demands (Krausmann et al., 2013; Laurance et al., 2014). Conversely, relatively warmer temperatures in the early part of the twenty-first century, high evapotranspiration rates, erratic rainfall, and increasingly severe droughts have deleterious consequences to farmland by reducing crop yields, resulting in an increase of marginal lands (i.e., farmland and wildlands with limited access to irrigation water and depleted soil nutrients) (Schlaepfer et al., 2017). These increasingly warm and dry conditions in regions with limited resources suggest future edaphic, biological, and climatic constraints for cultivation of C_3 and C_4 crops. Such conditions increase the need for seeking, selecting, and cultivating drought-tolerant crops, such as those found in the succulent *Agave* genus, which cope with drought through nocturnal CO_2 fixation and CAM photosynthesis (Borland et al., 2009, 2015; Stewart, 2015).

Current challenges in dry regions to cultivate and produce food in hot and water-limited conditions bear similarity to those that native people faced long ago during severe droughts in what is now the U.S. Southwest (Ingram, 2010). Irrigation water has always been a naturally limited resource in arid regions (Troyo-Diéguez et al., 1990). For dry regions, there is a need for sustainable agricultural strategies to optimize crop yields and irrigation water (Troyo-Diéguez et al., 1990). To cope with scarce availability of water, innovative, indigenous dry-farming strategies were developed anciently to produce food during droughts (Lightfoot, 1996). These dryland farmers irrigated with rainfall runoff by optimizing rainwater catchment and rewetting the landscape using manmade stone features, such as rock terraces and rock mulch (Wilken, 1972; Lightfoot, 1994, 1996). The indelible signature left by the historic use of rock terraces and rock mulching can be seen in ancient and modern societies in dry regions throughout the world. For example, in the Negev Desert of the Middle East, the nomadic Nabateans, who settled in the region around 600-300 BCE, built and used rock terraces, check dams, and rock mulching to irrigate and catch rainfall water (Stager, 1976; Evenari et al., 1982; Lightfoot, 1994; Ashkenazi et al., 2012). At the apex of Nabatean civilization, such terraces became the main dry-farming technology to cultivate olives (*Olea europaea*), pomegranates (*Punica granathum*), and apples (*Malus domestica*) (Ynnilä, 2007). Similar examples can also be found in ancient civilizations throughout the deserts of Africa, Europe, and Asia (Wilken, 1972; Lightfoot, 1994; Biazin et al., 2012). In the ancient Americas, rock-farming techniques were used in a variety of cultures and time periods (Marcus, 2006; Kennett, 2012). In the Andean region, from the times of the Huarpa civilization to that of the Incan (200 BCE to 1400 CE), rock-wall terraces were heavily relied on to cultivate potatoes (*Solanum tuberosum*), quinoa (*Chenopodium quinoa*), and corn (*Zea mays*) (Denevan, 2003; Chapagain and Raizada, 2017). Mayans in southern Mesoamerica were very effective in cultivating corn using rock terraces (Turner, 1976; Fischbeck, 2001; Webb et al., 2004). In central and northern Mesoamerica, Aztecs cultivated marginal lands with corn and agaves in a system called milpas (Evans, 1990; Zizumbo-Villarreal et al., 2012; Trombold, 2017). Ancient Pacific Islanders used rock mulching to harvest rainwater and to cultivate perennial crops, such as taro (*Colocasia esculenta*), in land with limited access to water (Stevenson et al., 1999; Wozniak, 1999; Ladefoged et al., 2013). Pre-Columbian Hohokam people, which inhabited the deserts of the American Southwest, also cultivated drought-tolerant agaves in marginal lands using rock-mulching (Fish et al., 1985; Fish and Fish, 1990, 1992; Gasser and Kwiatkowski, 1991).

Among historic dry-farming examples in the U.S., Hohokam agricultural dryland systems in central and southern Arizona are key to understanding applications of dry farming for other arid regions affected by drought. The Hohokam mastered desert farming (Fish and Fish, 1992). Their dry-farming techniques were adapted and designed to produce food in extended droughts and in the harsh Sonoran Desert climate. They implemented rock-mulching to catch rainfall water and successfully cultivate agaves to feed thousands of desert dwellers during water scarcity periods (Fish and Fish, 1990). Rock mulching turned into the primary strategy to shore up food production during droughts. *Agave* was the main crop that allowed for unabated cultural, social, and economic development in the region (Fish, 2000). As

in the prehistoric past, modern central and southern Arizona is a region constrained by the harsh Sonoran Desert climate. Here the applications of indigenous dry-farming agriculture, principally Hohokam rock mulching, opens the possibility for cultivating agaves in current and future droughts. It is our intent to portray *Agave* as a drought-tolerant crop, which can be cultivated through the application of rock mulching to harvest rainwater as a feasible and sustainable dry-land agriculture system for arid regions. The purpose of this paper is to summarize literature available on (1) studies on the ecophysiology of agaves under drought conditions, (2) dry farming using rock mulching to cultivate agaves, (3) ancient and modern-day uses of agaves, and (4) the potential of rock mulching and *Agave* cultivation in future droughts.

BIOLOGICAL TRAITS OF AGAVES KEY FOR ITS CULTIVATION IN FUTURE DROUGHTS

Nearly 75% of the continental biological diversity of the *Agave* genus can be found in Mexico and 13% in U.S. deserts (Gentry, 1982; Garcia-Moya et al., 2011). The *Agave* genus evolved biological and morphological traits that enable species to adapt to erratic, hot, and drought-changing conditions of arid regions (Silva-Montellano and Eguiarte, 2003). Morphological traits of agaves, such as their shallow root systems, distinct rosette shape, and curved leaves to maximize rainfall interception, evolved to efficiently use small amounts of atmospheric and soil moisture in water-limited environments (Martorell and Ezcurra, 2007). Such limited water and heat conditions negatively affect the physiological performance of domesticated C_3 and C_4 crops (Nobel and Jordan, 1983). Crassulacean acid metabolism (CAM) photosynthesis is the main biological trait that drives productivity of these plants in hot and water-scarce conditions (Lüttge, 2004; Borland et al., 2011). Photosynthesis of agaves relies on nocturnal stomatal opening and CO_2 gas exchange as a strategy to avoid high evapotranspiration rates and leaf water loss during daylight hours (Lüttge, 2004). Nocturnal CO_2 fixation is the primary trait agaves use to survive dry climates and to adapt to warm temperatures (Borland et al., 2009). In addition, above and belowground morphological traits (North and Nobel, 1991), such as leaf succulence, rain-hair roots, and fibrous root architecture enable agaves to adjust physiological processes to available soil-moisture levels and heat in the different seasons of dry regions (De Micco and Aronne, 2012).

Agaves are monocarpic plants with a long life cycle to maturation (Nobel, 1977). Differences in plant maturation can be observed within and between species, regions, cultivation practices, and degree of domestication (e.g., domesticated agaves, hybrids of agaves, or wild agaves) (Zizumbo-Villarreal et al., 2013). Generally, cultivated agaves require a few years or up to a decade to mature to flower, and typically more than a decade to mature to flower in the wild (Cervantes et al., 2007; Núñez et al., 2008).

Aboveground morphological traits of agaves (e.g., shape, size of leaves, and succulence) enable these plants to survive and adapt to deserts by providing protection and storing water in the leaf parenchyma (Orians and Solbrig, 1977; Cervantes et al., 2007; Núñez et al., 2008). Additionally, the rosette arrangement of the curved *Agave* leaves funnel rainwater to the plant and soil during the summer monsoon season, re-wetting their rhizomes and the soil in the root zone (Gentry, 1982). Furthermore, Martorell and Ezcurra (2007) hypothesized that the rosette trait can also trap atmospheric moisture in the form of dew and fog between leaves. The thick succulent leaves of agaves function as plant water storage for periods of scarce rain and soil moisture. Even after a period of several months, when soil moisture has reached the permanent wilting point, agaves will remain physiologically functional (Nobel, 2003).

The *Agave* root system is composed of shallow roots (mean root length: 8 to 20 cm) and rhizomes (Arizaga and Ezcurra, 2002; Nobel, 2003; Bautista-Cruz et al., 2007). Offset growth from rhizomes and aerial bulbils act as the main asexual propagation strategy of agaves. Such offsets can extend several meters from the plant in search of soil moisture (Gibson, 1996; Nobel, 2003). Shallow roots allow rapid soil moisture absorption from the soil surface, particularly from small amounts of moisture deposited after light rain events (North and Nobel, 1991). Fibrous *Agave* root systems maximize soil water absorption, particularly in well-drained sandy soils with limited capacity to retain moisture (Cervantes et al., 2007). In addition, in very dry soils, dehydration of suberized peridermal cells of mature *Agave* roots prevents water loss and desiccation of the root vascular system (North and Nobel, 1991). Additionally, these lignified roots anchor *Agave* plants to the soil. When rainfall occurs, water pulses from rain rehydrate *Agave* roots, which promotes emergence of new root hairs, thereby increasing hydraulic conductance of *Agave* root systems (Palta and Nobel, 1989). Rainwater stimulates growth of ephemeral root hairs, which are vital for rapid water uptake and replenishing of water in *Agave* leaves (North and Nobel, 1991; Huang and Nobel, 1992).

Wild and cultivated agaves flourish in arid environments and poor soils in marginal lands (Gentry, 1972; Cervantes et al., 2007; Núñez et al., 2008). Edaphic requirements include sandy soils with good drainage, 60% gravel content, and deep water tables (Cervantes et al., 2007). Particularly sandy loam soils with low salinity contents are optimum for healthy establishment of agaves. Agaves can be found growing in rocky soils in which temperatures can reach 70°C (Gentry, 1972; Nobel, 1994). Agaves typically perform well in soils with low nutrient content. Nitrogen levels in soils range between 31 and 35 parts per million (ppm) and low P between 2.6 and 3.0 ppm for optimal growth of agaves (Cervantes et al., 2007). Ideal growing conditions for agaves can be found in low-elevation mesic areas on hillslopes. In the Sonoran Desert of northwestern Mexico and southern Arizona, optimum elevation ranges for *Agave* growth have been observed between 800 and 1200 m above sea level (Gentry, 1972; Nobel and Hartsock, 1986; Núñez et al., 2008; Parker et al., 2014; Hodgson et al., 2019). However, agaves can also be found in the coastal areas of the Sonoran Desert in Mexico (Gentry, 1972; Cervantes et al., 2007; Núñez et al., 2008). Ideal precipitation

levels for agaves vary from tropical to dry regions (Gentry, 1982; Nobel, 2003). In arid regions, such as Sonora, Mexico and Arizona, USA, agaves can survive rainless seasons for several years (Nobel, 2003). Some regions with wild populations of *Agave* receive as little as 7 mm of rain and other regions receive as much as 762 mm or more of annual precipitation (Gentry, 1972, 1982; Nobel, 1976).

CULTIVATION OF AGAVES USING ROCK-MULCHING BY THE HOHOKAM

Who Were the Hohokam?

The Hohokam were pre-Columbian dryland farmers that established a flourishing civilization in what is now central and southern Arizona between 450 and 1500 C.E (Fish and Fish, 2008). Hohokam agriculture was constrained by the hot, dry climate, and the wide expanse of marginal lands in the Sonoran Desert (Fish and Fish, 1990). Drought and water availability for agriculture acted as definitive factors that influenced innovation in the agricultural and cultural development of the Hohokam (Rice, 1998; Hunt et al., 2005). These two factors shaped Hohokam irrigation and dryland agriculture in the desert, leading to the use of extensive irrigation-canal networks and rock mulching to cultivate agaves during periods of drought with erratic rainfall (Woodbury, 1961; Fish and Fish, 2012). Such approaches can be compared with dryland-farming systems observed in other advanced, prehistoric indigenous societies of Mesoamerica and South America (Doolittle, 1995; Fish and Fish, 2008). The irrigation canals of the Hohokam were similar to highly engineered Andean and Aztec irrigation-canal systems in that they were a pivotal factor in their cultural development and were designed to efficiently irrigate large areas of farmland, which led to substantial food production (Armillas, 1948; Bennett, 1948; Mitchell, 1973).

Irrigated crops formed the basis of Hohokam civilization and its economy. Efficiently distributed irrigation water from rivers and canals allowed large settlements to develop along the main rivers in the Phoenix Basin (Doyel, 2007). However, recurrent droughts at the beginning of the second millennia CE triggered periods of unstable food production, which changed agricultural strategies and the crops they cultivated (Fish and Fish, 1990). The Hohokam shifted to using more dryland farming and reliance upon rainfall for crop irrigation, resulting in less canal irrigation in the region.

During this period of recurring droughts, agaves were adopted as a crop to compensate for yield deficits during water shortages and as a supplement to irrigated annual crops (Fish and Fish, 1992, 2008; Anderies et al., 2008). The Hohokam primarily used rock piles to cultivate agaves, which enhanced their productivity during drought periods in the Sonoran Desert (**Figure 1**; Fish et al., 1985; Fish and Fish, 2012).

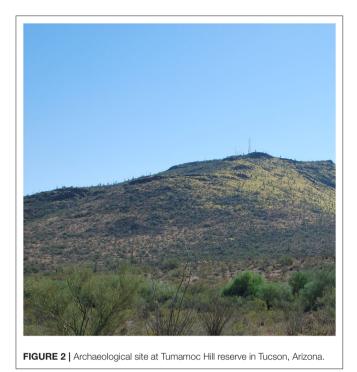### Dryland Farming Using Rock-Mulching to Cultivate Agaves

In the American Southwest, as in pre-Hispanic northern Mexico, the Hohokam implemented dryland agriculture strategies to

FIGURE 1 | Hohokam rock pile remains at Tumamoc Hill reserve in Tucson, Arizona.

cultivate *Agave* to ensure food security during droughts in the Tucson Basin (Fish et al., 1985; Anderies et al., 2008). A model of pre-Hispanic *Agave* cultivation by Anderies et al. (2008) suggests that *Agave* dryland farming was likely a strategy implemented by pre-Columbian groups to cope with climates with drought that reduced corn yields in the Sonoran Desert. The Hohokam adopted upland dryland farming on hillslopes using rock piles, terraces, and check dams to cope with low precipitation in the region (Fish and Fish, 1992). These structures allowed for the efficient use of rainwater to irrigate downhill floodplain crops and riparian vegetation (Fish and Fish, 1990). Rock piles and terraces were used to harvest rainfall runoff and to cultivate agaves (Fish and Fish, 1992).
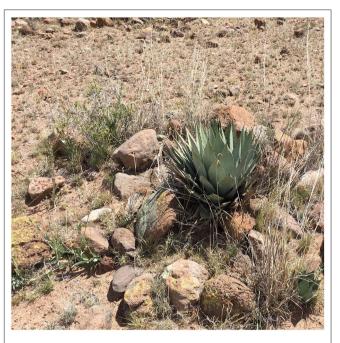
Historical remains of Hohokam rock piles and evidence of *Agave* cultivation and processing in roasting pits can be found at archaeological sites outside the Tucson, Arizona area in the Tortolita Mountains; the Salt Gila Basin; the community of Marana; Tonto National Forest; San Pedro Valley; and Tumamoc Hill Reserve (**Figure 2**; Masse, 1979; Crown, 1987; Ciolek-Torrello et al., 1997; Adams and Adams, 1998). One of the most representative Hohokam rock-pile fields, which was found in Marana and characterized by Fish and Fish (1992), consisted of at least 42,000 rock piles nested with 120,000 m^2 of terraces and check dams within an area of 500 ha. They calculated that the rock pile fields could have annually produced 102,000 *Agave* plants with an average yield of 40.8 Mg ha^{-1}. However, comparing average planting density (i.e., 1,000–3,000 plants ha^{-1}) of agaves (Cervantes et al., 2007; Núñez et al., 2008) in modern plantations in the Sonoran Desert in Mexico, with the rock-pile fields found in Marana, Arizona suggests

FIGURE 2 | Archaeological site at Tumamoc Hill reserve in Tucson, Arizona.

FIGURE 3 | Agave growing in ancient rock pile at archaeological site in Casas Grandes, Chihuahua, Mexico (picture courtesy of M. Searcy, 2019).

that *Agave* productivity in Arizona was possibly higher than previously calculated by Fish et al. (1985) (i.e., 102,000 *Agave* plants in 500 hectares). For example, between 1000-3000 *Agave angustifolia* plants ha^{-1} can be annually cultivated in Sonora, Mexico in grasslands with no irrigation (Cervantes et al., 2007). Similarly, McDaniel (1985) suggested a planting density of 2,000–2,500 of *Agave americana* plants ha^{-1} cultivated in grassland in southern Arizona. If the calculations of Cervantes et al. (2007) and McDaniel (1985) regarding *Agave* cultivation area and planting density are applied to the largest Hohokam rock-pile field in Marana, Arizona, the minimum planting density would be 1,000 plants ha^{-1} for 500 ha of rock-pile fields. As such, the Hohokam potentially had the capacity to cultivate nearly 500,000 agaves, which is at least five times more plants than previously estimated by Fish et al. (1985). However, commercial modern *Agave* cultivation differs from the cultivation strategies of the Hohokam. This example is only used to highlight the productive potential of the land to cultivate agaves in the region.

Hohokam Agaves

Agave plant remains in Hohokam rock-pile fields underscore the importance of rock mulch for modern cultivation of agaves in the region (Fish et al., 1985; Fish and Fish, 1990; Fish, 2000). Though agaves were no longer cultivated prior to the arrival of Europeans to the region, agaves still can be found growing in some rock-pile fields and archaeological sites in Arizona (Hodgson and Salywon, 2013; Hodgson et al., 2019). Minnis and Plog (1976) observed a relationship between the occurrence of wild *Agave parryi* plants with proximity and distribution of agaves growing at archaeological sites in the Apache-Sitgreaves National Forest, suggesting putative historic

cultivation of this *Agave* species in central Arizona. Similarly, Parker et al. (2010) observed genetic differences between putative cultigens of *A. parryi* and wild *A. parryi* plants at archaeological sites in central Arizona in the Mogollon Rim. Recently, a taxon, which was named *Agave sanpedroensis*, was discovered growing only in a rock-pile field west of Tucson, which is likely a relic of Hohokam cultivation (Hodgson et al., 2019). Living plants and dried tissue of *Agave* at rock piles and roasting pits have been found in Hohokam rock-pile fields at archaeological sites in southern and central Arizona (Fish et al., 1985; Adams and Adams, 1998; Fish, 2000; Parker et al., 2007; Fish and Fish, 2012).

Little is known about cultivation of agaves using rock piles outside of Arizona. Minnis et al. (2006) found little evidence of rock piles around the prehistoric archaeological site of Casas Grandes in Chihuahua, Mexico. However, ethnobotanists and archaeologists that visited archaeological sites near Casas Grandes in 2018 and 2019 found agaves growing in ancient rock piles and terraces, perhaps indicating ancient cultivation similar to that found in Arizona (W. Hodgson and M. Searcy, personal communication). In 2018, putative hybrids of *Agave palmeri* and *A. parryi* were found growing in a rock terrace in the Casas Grandes region in northern Mexico (W. Hodgson, personal communication). Likewise, in 2019, *Agave* hybrids, which were similar in appearance to those discovered in 2018 were growing in rock piles (M. Searcy, personal communication) (**Figure 3**). These recent findings suggest that cultivation of agaves using rock structures was likely more widespread than originally assumed. Such discoveries offer new avenues of research in the use of rock piles for prehistoric *Agave* cultivation.

AGAVE TRADITIONAL USES THROUGHOUT HISTORY, FOOD, DRINKS AND OTHER SUB-PRODUCTS

Uses in Ancient Times for Food and Fermented Drinks

Indigenous people in Mexico and the U.S. Southwest have used agaves as a source of carbohydrates and fiber for the past 10,000 years (Delgado-Lemus et al., 2014). Diversity in the *Agave* genus is largely concentrated in Mexico and the U.S. Southwest, and was cultivated mostly using dryland farming techniques, such as rock mulching using rainwater runoff (Lightfoot, 1994, 1996), widely throughout tropical and arid regions of Central and South America (Good-Avila et al., 2006). Beginning in pre-Columbian times, *Agave* was used for various purposes in what is now the U.S. Southwest, including beverages, ceremonial items, fiber-based products (e.g., clothing, footwear, containers, cordage, nets, etc.), food, medicine, and paint (Castetter et al., 1938). Over the span of several centuries, particularly during droughts, agaves were an important energy source that enriched the diets of indigenous people (Fish et al., 1985; Evans, 1990; Fish and Fish, 1990; Anderies et al., 2008).

The Hohokam were one of the few pre-Columbian indigenous groups in the U.S. Southwest that extensively used rock piles to cultivate agaves as a staple crop that ensured a reliable source of food, even during droughts (Fish et al., 1985; Dobyns, 1988; Fish and Fish, 1992). The Hohokam relied on the ability of these plants to concentrate sugars in stems and stalks through their long phenological cycle. Sugars in *Agave* are inulin-type polymers of fructose that concentrate in leaves, stems, and inflorescence stalks (Mancilla-Margalli and López, 2006; Urias-Silvas et al., 2008). However, removal of *Agave* stalks at the end of their life cycle induces sugar accumulation predominantly in the stem (Hodgson, 2001; Cervantes et al., 2007; Michel-Cuello et al., 2008). Inflorescence stalk emergence indicates plants have matured, and are ready to be harvested (Arizaga and Ezcurra, 2002).

Pre-Columbian indigenous people used roasting pits, also called earth ovens, to cook their food, but particularly to roast agaves (Walton, 1977; Fish et al., 1985; Cervantes et al., 2007; Perry and Flannery, 2007; Zizumbo-Villarreal et al., 2009). Roasting pits can reach temperatures between 150 and 200°C (Cervantes et al., 2007). Roasting *Agave* heads (or caudices) at this temperature enables thermal hydrolysis to break down carbohydrate polymers into sugar monomers, such as fructose and glucose, which are relatively easy to digest and ferment by yeast (Cervantes et al., 2007), making it possible to use agaves as a food source. Methods of cooking *Agave* heads using earth ovens share similarities (e.g., shape, diameter of 1.20–2.40 m, depth of 0.80–2.10 m) between indigenous groups across various regions, both in ancient and modern times (Cervantes et al., 2007; Towell and Lecón, 2010).

The practice of roasting agaves can be traced to its origins in pre-Columbian archaeological sites in central Arizona and northern Mexico (Fish et al., 1985). In Arizona, *Agave* roasting pits also can be found in rock pile-fields (Fish and Fish, 1992).

These roasting pits attest to the ancient use of roasted agaves and their cultivation in rock piles in the region. In addition, several documents from the Spanish colonial period recorded historic uses of roasted agaves by natives. Early colonial Jesuits from Spain, in what is now northwestern Mexico, recorded that agaves were used for medicinal purposes and were roasted for food by the Opata people in the Sonoran Desert (Gutiérrez-Coronado et al., 2007; Flores and Araiza, 2012). Similarly, in what is now central Mexico in the mid-sixteenth century, colonial Spaniards documented medicinal uses of roasted *Agave* by the Aztec people in the ethnobotanical compendium Codex Florentino (Williams, 1990; Díaz et al., 1993). Uses of roasted and fermented agaves for food were also recorded in the Codex Azcatitlan and Codex Boturini (Morán, 2008).

Modern Use of *Agave* as a Food Source

As indicated above, out of all the organs of agaves, the stem head produces the most edible biomass (Nobel, 2003). Inflorescences, leaves, and stalks can also be used for food and to feed cattle (*Bos primigenius taurus*), sheep (*Ovis aries*), and goats (*Capra aegagrus hircus*) (Gentry, 1972; Pinos-Rodríguez et al., 2006, 2008, 2009; Hartung, 2016; Mellado, 2016). Gentry (1972) indicated that inflorescences of some *Agave* species are edible. Moreover, Fuentes-Rodriguez (1997) and Gentry (1972) suggest that the raw leaves remaining after clipping leaves from *Agave* stems, commonly called jimado in Spanish, can be used to feed cattle. Pinos-Rodríguez et al. (2006) found that leaves, flowering stalk, and bagasse of *Agave salmiana* can be used as food and to increase body weight of sheep. In popular Mexican cuisine throughout the country, *Agave* leaves are also used to cover goat or lamb stew while being cooked in underground roasting pits.

Alcoholic Spirits and Drinks From Agaves

Aguamiel, pulque, and mezcal constitute the main beverages produced from agaves (Stewart, 2015). In order to produce aguamiel, an emerging inflorescence is cut out of the stem head. *Agave* sap, which is rich in sugars, accumulates in the remaining basin. The sap juice is subsequently siphoned out of the basin and prepared as non-alcoholic drink known as aguamiel. Fermentation of aguamiel creates pulque (Rivas, 1991), a commonly consumed, mildly alcoholic beverage in rural areas of central and southern Mexico (Enríquez-Salazar et al., 2017).

It has been estimated that pulque made of *Agave mapisaga, A. americana, Agave atrovirens*, or *Agave salmiana*, was consumed in approximately 2000 B.C. (Escalante et al., 2016). Although distilled *Agave* spirits like Tequila or mezcals are very popular in modern times, artisanal crafting and consumption of pulque remains alive in some regions of central Mexico.

Although drinks, such as aguamiel and pulque, are still consumed in modern times, these beverages have been somewhat replaced by distilled alcoholic drinks made from distillation of fermented sap of agaves (Garay and Aurea, 2008). Distillation technologies, such as the use of copper alembic stills to distill alcohol, were adapted to produce *Agave* spirits in Mexico by the Spaniards in the 1500s (Gutiérrez-Coronado et al., 2007; Towell and Lecón, 2010). In combination with a wide array of

distillation methods, the diversity of *Agave* species in the different regions and the various cooking and fermentation methods of *Agave* heads employed by tribes across Mexico enabled a rich diversification of *Agave* spirits throughout Mexico from various species (Walton, 1977).

Tequila is the most popular *Agave* spirit crafted in Mexico, and differs from commercial mezcal in that it is made exclusively from *Agave tequilana* var. Azul, which is also known as blue agave (Colunga-GarcíaMarín and Zizumbo-Villarreal, 2006; Vargas-Ponce et al., 2007). In contrast, mezcals are made from a wide diversity of agaves across Mexico. In addition, similar to some French wines, tequila has an appellation of origin (denominación de origen), which requires that blue *Agave* plants only be grown in certain states of Mexico that are believed to enhance the quality of tequila (Bowen, 2015). Tequila is mainly produced at an industrial scale following quality-control regulations compliant with national and international standards established by the Tequila Regulatory Council (Macías, 2001).

Despite climate change and political and economic changes throughout Mexican history, the tequila industry has experienced continual growth. For example, Walton (1977) reported 1.67 million liters of tequila were produced in 1960. Based on statistical data of total production of tequila from the Tequila Regulatory Council (2019), peak tequila production occurred in 2018 which coincided the highest production level ever reached over the past 23 years. In 1995, 104.3 million liters of tequila were produced, but increased to 309.1 million liters in 2018. Similarly, the Tequila Regulatory Council (2019) recorded that global consumption of tequila increased from 279 thousand tons in 1995 to 1,139 thousand tons in 2018. The Secretariat of Agriculture Livestock, Rural Development, Fisheries and Food (SAGARPA) in Mexico reported in 2017 that tequila, relative to mezcal, is the major product from *Agave* in an expansive growth phase in Mexico. Outside of Mexico, tequila is consumed mainly in the United States, Germany, Spain, France, and the United Kingdom. In addition, SAGARPA (2017) reported that the tequila industry generated approximately $27 million dollars from export revenue, which is predicted to increase to $28 million dollars by 2024 and $29 million by 2030. The mezcal industry has also experienced sustained growth from about 2.5 million liters in 1950 to about 20 million liters in 2010 (Martínez Salvador et al., 2012).

Sweeteners and Syrups

Fructose sugars extracted from blue agave have also been used as alternative sweeteners (Heyer and Crawford, 2009; Stewart, 2015). Despite disadvantages of a relatively long life cycle and the monocarpic habit of agaves compared with other annual and perennial crops used in the sugar industry, *Agave* sugars are used as high-quality sweeteners. This emerging product can potentially work as a companion to the tequila industry. As with *Agave* spirits, the sweetener industry uses *Agave* juices as feedstock (Heyer and Crawford, 2009; Narváez-Zapata and Sánchez-Teyer, 2010). Sugars from *Agave* juice, particularly fructose, are extracted through acid or enzymatic hydrolysis (Garcia-Aguirre et al., 2009; Ávila-Fernández et al., 2011; Soto et al., 2011). The fructose sugars are used as

additives in commercial *Agave* syrups, which are considered healthier sweeteners compared with sugar cane and high-fructose corn syrup (Hooshmand et al., 2014). The proportion of fructose in *Agave* syrup is significantly higher compared with the proportions in cane sugar and high-fructose corn syrup. Proportions of fructose to glucose are 50/50 in cane sugar (Glasziou, 1961); 55/45 in high fructose corn syrup (O'Brien-Nabors, 2001); and as high as 95/5 in *Agave* syrup (Garcia-Aguirre et al., 2009).

Modern Uses of Agave Fibers

Historically, *Agave sisalana, Agave fourcroydes* and *Agave lechuguilla* fibers have been used in the Mexican textile industry. Traditional uses of *Agave* fiber include ropes, twine, bags, mecapales, fabrics, brushes, and brooms (Colunga-GarcíaMarín and May-Pat, 1993; Kicińska-Jakubowska et al., 2012). Sisal is a hard fiber processed from the leaves of *A. sisalana*. Henequen fiber from *A. fourcroydes* and Tampico fiber (also called Mexican fiber) from *A. lechuguilla* have similar tensile and flexural properties as sisal fiber (Belmares et al., 1981; Kicińska-Jakubowska et al., 2012). More recently, *Agave* fibers have been used to reinforce industrial products, adding flexibility and strength to polymer-based composites (Joseph et al., 1999; Silva et al., 2010; Orue et al., 2016). Fiber-reinforced polymers have application in the aerospace, marine, automotive, military, and construction industries (Yilmaz and Arifuzzaman Khan, 2019). Compounds derived from *Agave* fibers, can also be used in synthetic drug manufacturing (Cushman et al., 2015). Steroidal saponins, tigogenin, and hecogenin are natural compounds extracted from *A. sisalana* leaves, which are used in the synthesis of steroidal hormones such as corticosteroids (Cripps and Blunden, 1978; Santos and Branco, 2014). Corticosteroids drugs like dexamethasone can be synthesized from tigogenin and hecogenin (Kongkathip et al., 1997; Santos and Branco, 2014) and may have application in treating respiratory-inflammatory conditions associated with COVID-19 produced by 2 SARS-CoV-2 (Al Saleh et al., 2020; McIntosh, 2020; Zhang et al., 2020).

Potential Uses of Agaves for Bioenergy

Agaves have also been proposed as a biofuel crop due to their relatively low lignin content (Somerville et al., 2010; Davis et al., 2011). The high lignin content of C_3 and C_4 biofuel crops reduces the efficiency of converting sugars into bioethanol (Somerville et al., 2010). Lignin percentages in agaves range between 3 and 15% (Iñiguez-Covarrubias et al., 2001; Li et al., 2012; Delfín-Ruíz et al., 2019), and can be more efficiently processed to produce sugars than C_4 crops used in the biofuel industry (Somerville et al., 2010).

Many crops used in the biofuel industry require high amounts of irrigation water, generating controversy related to their environmental footprint (Somerville, 2007; Moore et al., 2014). Agaves require much less water than C_4 crops, such as corn, to produce biomass, and the superior quality of ethanol derived from *Agave* compared with corn makes agaves an attractive alternative (Yan et al., 2011). In addition to the low lignin content

of *Agave*, CAM metabolism enables their growth in marginal lands and resilience to drought (Davis et al., 2011).

One challenge in the widespread use of agaves in the biofuel industry is the lack of agronomic knowledge for its cultivation, as well as the underlying ecology and climatic conditions of regions where this crop may be suitable (McDaniel, 1985). Lewis et al. (2015) suggested the U.S. Southwest, particularly Arizona, as one region for *Agave* cultivation for the biofuel industry, due to its suitable climate. Another constraint on *Agave* production involves the large amount of annual plant biomass needed to supply enough raw material to make it profitably sustainable as a bioenergy crop (Balan, 2014).

According to Escamilla-Treviño (2012), commercial cultivation of agaves for biofuel in the U.S. has been constrained mainly by the risk of low-temperature crop damage. For example, cultivation of species with a frost tolerance between −2 and −4°C, such as *A. tequilana*, *A. fourcroydes*, *A. angustifolia*, *A. salmiana*, and *A. sisalana* (Nobel, 2003), could be limited even in Arizona, where nocturnal low temperatures below 0°C occur throughout the winter season. Agaves could be genetically engineered to improve traits, which would allow for better adaptation from temperate to xeric environments, which would enable agaves to be widely cultivated in marginal environments in the U.S. (Yang et al., 2016). Another approach could be to use *Agave* species that have relatively wide cold tolerance, such as *A. americana* and *Agave utahensis*, which have been reported to adapt well to cold and hot temperatures in the region and can tolerate temperatures between −8 and −11°C (Nobel and Jordan, 1983; Escamilla-Treviño, 2012; Davis et al., 2017). Moreover, species putatively cultivated by the Hohokam in pre-Colombian times, including *A. palmeri*, *A. murpheyi*, *A. parryi*, and *A. sanpedroensis*, could potentially be used as crops in the future because they are endemic and well-adapted to hot summers, cold winters, and the dry climate of the Sonoran Desert (Adams and Adams, 1998; Parker et al., 2010; Hodgson and Salywon, 2013; Fish and Fish, 2014; Hodgson et al., 2019).

ROCK PILES TO CULTIVATE AGAVES IN MARGINAL LANDS

Rock Piles as Dryland Farming System for Agaves in Marginal Lands

Agave rock-pile fields are a cultural and agricultural legacy of the ancient Hohokam tribe in the Sonoran Desert (Hodgson et al., 2019). Rock piles are specialized features associated with the ancient practice of *Agave* cultivation in marginal lands (Dobyns, 1988; Fish and Fish, 1990, 1992, 2012, 2014; Sandor and Homburg, 2017). Because CAM metabolism enables agaves to grow well in water-limited environments and in nutrient-poor soils (Gentry, 1982; Nobel and Valenzuela, 1987; Nobel, 1991, 2003; Garcia-Moya et al., 2011), *Agave* was and is a well-suited crop for marginal lands. Prehistoric groups from central and southern Arizona lived in marginal lands with limited access to irrigation water (Fish and Fish, 1992). Rainfall was the primary source of water to irrigate agaves in rock piles. Rainwater in rock-pile fields was harvested in two ways: through the interception of

rainfall hitting rocks and from rain-water runoff (Crown, 1987; Fish and Fish, 1992; Lightfoot, 1994, 1996).

Rock piles were built on downhill slopes such that the inclined angle mitigated downward runoff and enabled rock piles to reduce erosion and increase fertility of *Agave* fields (Fish and Fish, 1992; Sandor and Homburg, 2011). In such rock piles, rainwater generally flows along soil slopes, and upon intercepting rock piles, it slows down, leading to increased soil moisture beneath the rock piles (Fish and Fish, 1990, 1992; Homburg and Sandor, 2011). The reduced flow of rainwater leads to less gully formation. Likewise, sediments and minerals were mixed in the rainfall runoff and deposited underneath rocks. According to Homburg and Sandor (2011), the accumulation of minerals under rock piles improved the texture of the soil-surface horizons and increased soil moisture retention capacity. The minerals, sediments, and organic matter deposited below rock piles were a source of C, N, and P, which provided a source of soil fertility for agaves cultivated by ancient indigenous groups, such as the Hohokam.

Agave Species Likely Cultivated by the Hohokam in Rock Piles

Evidence of cultivation of different *Agave* species in rock piles includes plant tissue, such as spines and fibers at nearby roasting pits and artifacts found in rock-pile fields, which were likely used to process and harvest agaves, such as tabular knives and scrapers (Cantley, 1991; Fish and Fish, 1992; Ciolek-Torrello et al., 1997). Among *Agave* species native to Arizona, *A. murpheyi* and *A. sanpedroensis* have been recognized as species that were cultivated in rock piles by the Hohokam (Adams and Adams, 1998; Parker et al., 2007; Hodgson et al., 2019). Moreover, researchers have identified *Agave yavapaiensis*, *Agave verdensis*, and *Agave delamateri* as pre-Columbian *Agave* cultigens (Parker et al., 2007; Hodgson and Salywon, 2013). Similarly, *A. parryi* has been associated with archaeological sites and dryland farming in Arizona (Minnis and Plog, 1976; Parker et al., 2010, 2014). Evidence of other cultivated plants used by the Hohokam include pollen grains of corn and cotton, which were found in rock piles (Crown, 1987; Fish, 1988; Bohrer, 1991). Other native species, such as *Opuntia spp.*, *Carnegia gigantea*, *Chenopodium* spp., *Amaranthus* spp., *Trianthema portulacastrum*, *Spharalcea ambigua*, *Boerhaavia spp.*, and cholla (*Cylindropuntia fulgida*) have been found to populate rock-pile fields in archaeological sites (Fish et al., 1986; Crown, 1987; Bohrer, 1991; Hodgson et al., 2019).

POTENTIAL BENEFITS OF USING ROCK PILES TO CULTIVATE AGAVES

Rock Pile Fields for Agaves and Their Environments

While rock piles can be found at archaeological sites throughout the southwestern U.S. and northwestern Mexico, most are located in south-central Arizona (Fish et al., 1985; Fish and Fish, 1990, 1992), providing an ideal setting for modern *Agave* cultivation that could incorporate aspects of prehistoric rock-pile fields. Rainfall and temperatures at rock-pile fields in Marana,

Tucson, and San Pedro Valley, Arizona, whose elevations range between 600 and 900 m above sea level, suggest that Hohokam agaves were cultivated in an optimum environment that balanced temperature, rainfall, and soil moisture (Fish and Fish, 1990, 1992; Cantley, 1991; Hodgson et al., 2019). This unique balance likely maximized productivity of agaves, even in the dry and harsh conditions of the region.

Different studies using the environmental productivity index developed by Nobel for agaves (Nobel and Hartsock, 1986; Nobel and Quero, 1986; Nobel and Valenzuela, 1987; Garcia-Moya et al., 2011) found, in general, that mesic environments, such as archaeological sites with Hohokam rock piles, can lead to improved *Agave* productivity. The index indicates that CO_2 uptake and productivity of agaves is greater at elevations between 600 and 1200 m above sea level. In addition, Woodhouse et al. (1980) found that agaves are less productive when cultivated on steep slopes. Hohokam rock-pile fields occur more frequently on softly inclined slopes, which have higher rainfall moisture interception, and less negative soil water potentials than found on relatively steeper slopes (Cantley, 1991; Fish and Fish, 1992). Such conditions possibly promoted better interception of photosynthetic radiation and rainfall, which would have led to enhanced CAM photosynthesis and biomass of agaves. Understanding Hohokam rock pile field environments can help to identify potential locations to cultivate agaves, even during severe drought events. However, more information needs to be sought out to determine the agricultural limitations and future applications of rock piles in modern times.

Soil-Water Dynamics Under Rock Piles

Hohokam rock piles functioned as a type of mulching that reduced soil evapotranspiration and used rainwater to increase soil moisture content underneath rocks (Doelle, 1978; Fish et al., 1985; Fish and Fish, 1990, 1992; Lightfoot, 1996). The positive effects of available moisture in agaves have been observed in different experiments. In an experiment with *A. deserti*, Jordan and Nobel (1979) observed that rainfall and soil moisture act as the most important factors influencing plant mortality in their first year of establishment. They also found that rainfall stimulated increased succulence, increased leaf growth, and helped modulate nocturnal CO_2 gas exchange and water-use efficiency of first-year plants. Davis et al. (2017) found that irrigation increased efficiency of nocturnal CO_2 uptake of *A. americana*. Similarly, Nobel et al. (1989) observed that irrigation doubled CO_2 uptake of *Agave lechuguilla* and enhanced aerial and root biomass. Lightfoot (1996) and Sandor and Homburg (2011) hypothesized that the moisture harvested underneath rock piles from rainwater improved cultivation of crops, including *Agave*, in rock piles (Fish and Fish, 2014). In an experiment using agaves in rock piles conducted in different locations in central and southern Arizona, Fish and Fish (2014) found that seasonal rains replenished soil moisture below rock piles, which improved survival rates of *A. murpheyi* and *A. americana*. Nobel et al. (1992b) reported that after watering rocks with 10–30 mL of water, soil volumetric water content increased below rocks for a period ranging between 13 and 19 days, leading to increased nocturnal CO_2 uptake of *A. deserti*.

While moisture underneath rock piles likely enhanced *Agave* biomass productivity, Eickmeier and Adams (1978) indicated that available water and air temperature are the two most influential factors that affect *Agave* carbon assimilation. Although day-night temperature is an important factor in *Agave* nocturnal CO_2 uptake, as observed with *A. angustifolia* and *A. americana* (Holtum and Winter, 2014), soil moisture governs biomass productivity of agaves (Huang and Nobel, 1992). Nobel and Quero (1986) indicated that available soil moisture in summer and fall in the Sonoran and Chihuahuan Deserts acts as the driving factor that stimulates biomass of *Agave* plants by promoting emergence of new leaves, development of large aerial shoots, and enhancement of root hydraulic conductance. In addition, Nobel (1976) observed that leaf size and soil water content correlated with higher nocturnal CO_2 uptake of *A. deserti*. However, the benefits of increasing soil moisture by using rock piles needs to be further explored through additional lab and field experiments.

Soil Temperature Underneath Rock Piles

Cool temperatures below rock piles can reduce heat stress and desiccation of roots of *Agave* plants (Huang and Nobel, 1992). Since daily soil temperatures in the Sonoran Desert can reach 75°C (Nobel, 2003), rock piles can reduce soil-moisture evaporation rates (Sandor and Homburg, 2011), and also work as a barrier to reduce interception of solar radiation, which leads to cooler diurnal soil temperatures relative to that found in exposed soil (Wilken, 1972). Studies made on the thermal properties of rock piles in *A. deserti* and *A. americana* illustrate the advantages of rock piles as insulation to diurnal hot temperatures. Palta and Nobel (1989) observed that low soil temperatures underneath rocks positively affected *A. deserti* root respiration and reduced root dryness. Nobel et al. (1992b) measured *A. deserti* roots underneath boulders or rock fragments and compared roots of agaves growing in exposed soils and found that low temperatures and less-negative soil water potentials underneath rocks increased root number, thickness, and length.

Kaseke et al. (2012) found that convective heat transference of rock mulch can keep soils cooler during the day and increase nocturnal soil temperatures. However, since little is known regarding patterns of diurnal and nocturnal temperatures underneath and within Hohokam rock piles, characterization of such properties is necessary in similarly arranged rock piles. In addition, experimentation is needed to characterize nocturnal convective heat transference underneath rock piles, and the level of nocturnal CO_2 uptake of agaves in rock piles.

Insulative properties of rocks and their effect on temperatures below rock piles likely have a positive effect on symbiosis of microbes with agaves (Cui and Nobel, 1992). A study on the effects of soil temperatures on vesicular-arbuscular mycorrhizae infection found that soil temperatures around 25°C increased yields of *Sorghum bicolor* and *Triticum aestivum* due to high colonization of roots by mycorrhizae (Fabig et al., 1989). Little is known, however, about the effect of Hohokam rock-pile temperatures on the soil microbiome and their associated benefits. Nevertheless, the *Agave* rhizosphere is diverse in prokaryotic and fungal microorganisms, and is

correlated with the hosting capability of agaves and their adaptions to arid climates (Coleman-Derr et al., 2016). Symbiosis of *Agave* roots with soil microbes enhances root hydraulic conductance and nutrient uptake, particularly solubilizing P. Cui and Nobel (1992) observed that colonization of *A. deserti* with mycorrhizae improved hydraulic conductance, uptake of P in roots, and P allocation in leaves. In addition, colonization of mycorrhizae positively correlated with enhanced CO_2 uptake of *A. deserti*. Plant symbiosis with arbuscular mycorrhizae, ecto-mycorrhizae, ericoid mycorrhizae, and various bacteria contributes to increased uptake of N and P in the form of phosphates (Mensah et al., 2015). In a study where endophytic bacteria were isolated from the base of *A. tequilana* plants, Martínez-Rodríguez et al. (2014) identified the presence of 300 strains of bacteria with different capacities and benefits, such as N fixation, P solubilization, auxin production, and antagonism against *Fusarium oxysporum*.

Soil-Based Nutrients Underneath Rock Piles

Agaves in the wild are well-adapted to arid regions and generally perform adequately in rocky, nutrient-poor soils (Gentry, 1972, 1982). However, soil-based nutrients underneath rock piles (Homburg and Sandor, 2011; Sandor and Homburg, 2017) can bolster *Agave* primary productivity (Nobel et al., 1992a). Soil research by Homburg and Sandor (2011) suggests that the use of Hohokam rock piles enriched C, N, and available P to agaves due to organic-matter accumulation. Soil nutrient accumulation underneath Hohokam rock piles possibly occurred due to runoff, microbial decomposition of organic matter, or soil bioturbation. The available nutrients below rock piles likely enhanced the physiological response of agaves to drought and extreme temperatures, and improved growth and productivity. However, it is necessary to assess the dynamics between soil-based nutrients underneath rock piles with *Agave* nutrient assimilation to more fully understand the benefits afforded by rock piles to *Agave* productivity. In addition, agricultural parameters, such as soil pH levels, soil electric conductivity, and nutrient cycling in the soil beneath rock piles, need future research.

Nutrients in the soil under rock piles, as observed by Homburg and Sandor (2011), contributed to the productivity of cultivated agaves. Available nutrients in the soil assist in the productivity of agaves (Nobel et al., 1992a). Nobel et al. (1988) observed that fertilization with N, P, K, and B enhanced growth and nocturnal CO_2 uptake of *A. lechuguilla*. Similarly, irrigation, in combination with fertilization with N, P, and K, increased foliar leaf area, leaf number, and concentration of sugars, particularly fructose and glucose in *A. tequilana* and *Agave potatorum* (Martínez et al., 2012; Zúñiga-Estrada et al., 2018). Valenzuela and Gonzalez (1995) found that fertilization of *A. lechuguilla* and *A. tequilana* with P and N increased leaf area. Similarly, for *A. deserti*, Nobel et al. (1989) observed that fertilization promoted leaf growth and high rates of CO_2 uptake, which led to high biomass accumulation.

Opportunity for Researching Agaves in Rock Piles

Relict rock piles at archaeological sites represent a valuable agricultural example of how the Hohokam made marginal lands productive by cultivating agaves during severe droughts. While a number of archaeologists reported that rock piles were the main dryland-farming strategy used by the Hohokam to cultivate agaves (Masse, 1979; Fish et al., 1985; Crown, 1987; Dobyns, 1988; Fish and Fish, 1990, 1992; Cantley, 1991; Lightfoot, 1996; Sandor and Homburg, 2011), little is known about the agronomic potential and applications of rock piles in modern *Agave* cultivation. To bring to light possible uses of rock piles, it is necessary to sort through what has been published regarding the environmental details of rock-pile fields in order to experimentally replicate these ancient agroecosystems.

Experiments that assess cultivation, pest management, and the physiological responses of agaves using rock piles are needed, particularly to observe plant productivity, CO_2 uptake, temperature requirements, and soil-plant water relations in rock piles. In addition, characterizing the hydrothermal properties of rock piles requires examining how they can preserve soil moisture and modulate soil temperatures. The microbiome and fauna of rock piles are additional factors that could potentially enhance nutrition, improve water status, and contribute to general plant health. Microbiomes in rock piles can positively impact plant health of agaves in future droughts, particularly in preventing pests and disease. Future research is needed on the environmental, social, and economic impacts of using rock piles to cultivate agave, particularly in the continually changing and fragile agroecosystems of dry regions.

CONCLUSIONS

Further experimentation and development of innovative agricultural strategies is crucial to the use of agaves as a crop under scenarios of severe drought and global warming. Throughout history, agaves have been used as commodities for food (Anderies et al., 2008; Delgado-Lemus et al., 2014), beverages (Walton, 1977; Stewart, 2015; Escalante et al., 2016), and fiber (Colunga-GarcíaMarín and May-Pat, 1993). In modern times, agaves continue to be used for such purposes, but are now also used as substrates for sweeteners (Heyer and Crawford, 2009; Stewart, 2015), biofuels (Somerville et al., 2010; Davis et al., 2011), synthetic drugs (Santos and Branco, 2014; Cushman et al., 2015) and industrial materials (Silva et al., 2010; Orue et al., 2016). We suggest dryland farming of *Agave* as a means to minimize the use of irrigation water and sustainably maintain crop productivity in arid regions.

Current challenges to successful cultivation of agaves, such as low rainfall and excessive heat in arid regions and marginal lands, are similar to those that prehistoric, indigenous farmers faced during droughts in the Sonoran Desert. The

pre-Columbian Hohokam were skilled in the use of rock piles to cultivate agaves during droughts (Dobyns, 1988; Fish and Fish, 1992). These rock piles acted as a mulch that harvested rainwater moisture, preserved soil moisture, reduced soil evapotranspiration, and insulated soil in their immediate environs. Despite the lack of empirical data, moisture harvested during the monsoon season beneath and around rock piles likely decreased drought stress, stimulating biomass productivity of agaves.

The use of rock piles for *Agave* cultivation promises ecological benefits, such as minimizing soil erosion and maximizing crop productivity in marginal lands with minimal input of chemical fertilization and pesticides

Rock pile cultivation of agaves is promising, but it requires field-based research to characterize their productive potential. More research is also needed to understand how the Hohokam rock-pile system could be used to cultivate crops other than agaves. However, with even from the little that is known, rock piles provide a sustainable crop-production-technology alternative for efficient use of water in dry areas and to revive cultivation of agaves in limited-resource environments in the region.

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