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Analyzing the Impact of Agave Cultivation on Famine Risk in Arid Pre-Hispanic Northern Mexico

John M. Anderies · Ben A. Nelson · Ann P. Kinzig

Abstract Cultivation of agave was common in pre-Hispanic northern Mexico and the American Southwest, and scholars generally accept that it was a strategy to ensure food supply during years of drought when the maize crop failed. Some even suggest that incorporating agave cultivation make large, nucleated settlements possible in arid northern Mexico ca. 500–900 CE. Yet the environmental circumstances under which farmers could reasonably expect such a strategy to decrease the chances of agricultural failure are not well understood. We explore the potential of this crop complementarity by assessing the risk of famine-induced migration events in different idealized environmental settings. We use Monte Carlo simulation to analyze a simple discrete-time, age-structured stochastic model for maize and agave agroecology, deriving the climatological conditions under which agave could have significantly reduced the probability of short- and long-term famine events. Investments in agave production made the most sense where average annual rainfall was between the levels that would ensure maximum maize yield and those that would mean loss of the maize crop due to drought-related mortality. Cultivating agave had little impact on famine risk at high (maize yields sufficient) and low (failure of both maize and agave) rainfall levels. Perhaps more surprisingly, it had its highest impact at moderate rainfall levels when variance in rainfall was relatively low. While a higher variance in rainfall increased the number of 'good' years for maize—where production would exceed demand and allow for storage—it also increased the probability of simultaneous failures in both agave and maize production. These findings are difficult to apply to specific times and places in the past, because rainfall distribution in complex, environments change, and it is difficult to take all relevant human interventions into account. The analysis does, however, offer support for the proposition that agave cultivation could have significantly enhanced survival probabilities of large, nucleated settlements in certain circumstances. It remains for further study to identify such circumstances more precisely geographically and temporally.

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Introduction

By 500 CE, inhabitants of the modern states of Zacatecas and Durango, Mexico, subsisted on a classic Mesoamerican triumvirate of maize, beans, and squash (Turkon 2004). This crop mix provided a complement of critical human nutrients, largely supplanting meat as a protein source. Contemporary subsistence farmers still depend on a similar mix, consuming 560–830 kg of maize per household per year, supplying 50% of their calories (López Corral and Urñuela y Ladón de Guevara 2005). This subsistence base probably developed first among peoples occupying lowland regions by around 3500 BCE and gradually spread to the mountainous valleys of the Mexican Central Plateau, eventually making its way north to desert areas in Northwest Mexico (Blake *et al*. 1992; Flannery 1986; Fritz 1994; Pohl *et al*. 1996) and the American Southwest (Wills 1993; Huckell 1995). During the period 500–900 CE, farming populations aggregated at unprecedented scales in widely separated arable patches along the foothills of the Sierra Madre Occidental (Kelley 1971).

Archaeologists have imagined this wave of aggregation as a colonization process in which well-established archaic central Mexican states took advantage of economic opportunities in the north, expanding the area of Mesoamerican civilization. Following indigenous accounts given to the Spaniards in the sixteenth century, Jiménez-Moreno (1959) and Braniff and Hers (1998) suggest a diaspora upon the breakup of the huge city of Teotihuacan, now thought to have occurred ca. 600 CE. Armillas (1964) proposed that the founding of northern population centers such as La Quemada was driven by climatic change that made it possible for central Mexican lords to exploit the land and labor of the northern valleys. Weigand (1977) proposed that the colonists were primarily interested in rare mineral resources. Others, such as Jiménez-Betts and Darling (2000), have argued that the northern centers arose, in part, through mutual interactions between elites of northern and central Mexico. There is as yet no published paleoenvironmental data with which to evaluate these competing (though not mutually exclusive) propositions.

Because of the region's aridity, vulnerability to famine probably was an issue for early northern Mexican maize farmers (Gunn and Adams 1981; Armillas 1964; Parsons and Parsons 1990; Sauer 1963). The northern contexts provided less annual precipitation, greater interannual variability in rainfall, and greater probability of extended drought than those in which maize farming originally developed. Maize farming did allow for larger population concentrations relative to a wild foods subsistence base, but northern groups were vulnerable in some periods to severely reduced crop yields, especially in maize, which is considerably more susceptible than beans to drought (Brouwer and Heibloem 1986). Armillas (1964) suggests that the abandonment of northern regions of Mexico, now known to have occurred ca. 900 CE, was due to the dry conditions. Coe (1994) asserts that populations in the north were driven "by drought and desperation" back to the south. Farmers in the study area today, with evolved maize varieties, report that they can count on good yields only about 2 years in 10 (Nelson 1992).

Sauer (1963) and Parsons and Parsons (1990) argue that a drought-adapted subsistence technology had to be developed for the arid conditions. They point to agave cultivation as a possible solution to the recurrent droughts that are envisioned during the northward expansion of Mesoamerican civilization. Anthropologists and archaeologists have documented several technological strategies used by people in other arid settings, including irrigation (Howard 1993), terracing (Fisher *et al*. 1999) food sharing (Hegmon 1996), mobility (Nelson and Anyon 1996; Nelson and Schachner 2002), and crop storage (Young 1996; Seymour 1994). Agave cultivation was thus one risk management strategy among many. Yet, based upon the abundance and diversity of agaves, together with the documentary and technological evidence for their exploitation, the Sauer-Parsons' hypothesis seems worthy of systematic evaluation. Berger (1915) lists a total of 274 species of wild agave; Trealease (1910, 1911) lists 186 for Mexico alone [both cited in Castetter *et al*. (1938)]. Nahua speakers distinguished 17 species of agave (which they called *maguey*), and the Otomi today distinguish 11 (Zorrilla and Batanero 1988). Some of the Nahuatl names recognize the properties of different species for different products, e.g., roasted hearts, fine thread, aguamiel (the sweet nectar extracted from the heart of the plant). Partly because of discrepancies between indigenous and European taxonomies, it is not easy to determine precisely which species were cultivated prior to the arrival of Europeans.

It is well established, however, that agave was cultivated at pre-Hispanic sites in central and northern Mexico and the American Southwest (Evans 1992; Fish and Fish 1992; McClung de Tapia *et al*. 1992; Minnis and Plog 1976; Phippen 1999; Trombold 1985). Evidence demonstrating agave cultivation archaeologically is found in many sites dating from ca. 200 CE onward, including tools such as discoidal scrapers and trapezoidal-shaped ground stone implements, close analogs to ethnographically observed implements for sap and fiber extraction respectively (Parsons and Parsons 1990, pp. 291–292, 298–300). Additional evidence comes in the form of rock piles and roasting pits containing charred agave fragments (Fish and Fish 1992; Van Buren *et al*. 1992). The interiors of a certain class of ceramic vessels at La Quemada are frequently acid-etched, a likely indicator of having contained pulque (*Nahuatl octli* or *neuctli*, a traditional alcoholic beverage). Also at La Quemada, although maize is ubiquitous in middens (Turkon 2004; Weintraub 1992), systems of terraces were built in areas too dry to support maize. The discoidal-shaped scrapers have been found in association with these terrace systems (Trombold 1985; Nelson 1992) and the trapezoidal-shaped ground stone implements in residential areas (Nelson 1992). Agave phytoliths are also found in the sediments trapped by these terraces (Trombold and Israde-Alcántara 2005). Elder occupants of the region reported to Nelson (1992) that they historically had planted agave as a backup resource when maize was in short supply, as they did in 1915 when Mexican revolutionary forces decimated their maize stores.

Given the life history characteristics of agave, few would disagree that people cultivated agave, at least in part, to supplement maize yields as a risk reduction strategy in a harsh and highly variable environment. This general idea has a modern analogue in the advice of portfolio managers to combine a diverse set of assets, including stocks and bonds, to reduce financial risk. This general statement, however, is not particularly insightful or useful in practice. Which and how much of each type of asset should be held to hedge against particular types of exogenous financial variation? What are the costs of managing such complex portfolios? Such specific questions apply equally to the case of combining food production strategies. How much effort should be directed toward agave and maize cultivation? What are the costs? Under what environmental circumstances is it worth cultivating agave? What, exactly, are the benefits?

These specific questions are the focus of this paper. In particular, we ask how many migration events due to famine might have been avoided by supplementing maize production with agave. How does this number depend on climatic variables, and the types and amount of agave cultivated? To address these issues, we model the caloric output from maize and agave cultivation over time under a range of precipitation conditions. We compute the frequency of famine events of 1, 2, 3, 4, 5 and greater than 5 years duration in a 100-year period and examine how the distribution of such events changed under different rainfall scenarios. This modeling exercise provides a measure of the degree to which adding agave to the repertoire of cultigens may have permitted continuity of occupation over centuries without other infrastructural change. This is obviously an oversimplification of the actual situation given the range of options open to pre-Hispanic northern Mexican farmers. However, our simplified characterization of the situation captures the essence of a strategy that couples a faster growing, less drought tolerant cultigen (maize, a riskier, though potentially higher-yielding species whose financial analogue is a stock) and a very slow growing, more drought tolerant species (agave, a less risky, lower yielding species whose financial analogue is a bond) to better cope with environmental variation. We do not expect that agave contained all necessary nutrients for optimal health. We imagine that wild foods may have supplied some of these nutrients during periods of low maize yield and that some people may have been malnourished. Our expectation is that agave may have permitted pre-Hispanic arid-lands farmers to temporarily bridge periods of low maize yields, making the maize strategy as viable as it might have been in better-watered areas such as the lake zones to the south of the study area.

Agave has many uses, including the making of *pulque*, clothing, rope, baskets, nets, and other items (Parsons and Parsons 1990). Beyond enhancing survival probabilities, the agave fields were a rich resource for a range of purposes from technological to political. For example, pulque was used in feasting, which was such a powerful sociopolitical strategy in Mesoamerica that the rituals, beverages, and containers associated with feasting were recruiting tools for political leaders (Clark and Blake 1994). One need not dichotomize agave production as being either for alimental or non-alimental purposes, since the same plants could produce both fiber and edible material in approximately equal proportions, according to the estimate of Fish *et al.* (1992). Moreover, food-stressed populations would probably forgo some of the more exotic uses of the plant in lean years.

Simple Model of a Maize-Agave Subsistence Strategy

In order to explore the potential of agave cultivation to enable populations to survive extended periods of drought, we developed a simple model of a subsistence economy based solely on the cultivation of maize and agave. Because it is difficult to estimate the precise yield and demand characteristics for agave and maize under different environmental circumstances, we develop our model based on *relative* quantities. For example, Fish *et al.* (1992) have estimated 10,000 harvested plants would meet the caloric needs of 155 people, while Leach (2007) questions their figures. Leach points out only about half of the calories produced by an agave plant are edible, and also that Fish et al.'s estimates of the weights of agave hearts may be rather high. Thus, their inferences about the human population that can be supported by a given number of agave plants may be an upper bound. Our model does not depend on knowing how many edible calories would be produced per unit of land. If the actual value of land needed is twice or more that estimated by Fish *et al.*, as Leach suggests, our results are not affected because we assume that achieving certain yields relative to consumption needs was within the technological and labor constraints of the population. In other words, lower yields would merely mean greater planting investment in our model. The intent of the model is to capture the basic attributes of such a system and especially to explore its potential output under a range of precipitation (climatic) regimes. As mentioned above, the idea of maintaining productivity in an uncertain environment through the management of a portfolio of different productive assets is ubiquitous in the field of finance. A subsistence strategy based on agave (bond) and maize (stock) is an example of a basic asset portfolio. It is this direct correspondence between physical and financial assets that motivates the model.

The performance of the maize-agave portfolio depends on the agroecology of these plants. Several different varieties of both maize and agave have been cultivated in the study region. We made no attempt to formalize a model for specific varieties or take into account the many subtleties of actual maize or agave cultivation systems. Instead, we have treated maize and agave as two different classes of agricultural products with general characteristics that differ mainly in their response to water availability. In formulating a model for productivity for each, we wanted to highlight the following similarities and differences:

1. Both maize and agave are assumed to be primarily limited by water (and not by other potential limiting factors such as light or nutrients). Thus, growth rates (yields) are determined by annual precipitation.
2. Both young agave plants and maize plants can be killed by single-year drought. Specifically, agave plants are assumed to die if annual rainfall drops below a certain critical level during the first 3 years of their life[1]; the annual maize crop will die if rainfall drops below a threshold level for a given year. Further, agave is assumed to be more drought resistant than maize; it takes more severe droughts to kill young agave plants than maize plants ($\underline{r}_j < \underline{r}_m$ in the formal model, see definitions in Table 1 and Figs. 1 and 2 for a physical interpretation).
3. Because agave is a perennial and maize an annual, depressed agave yields will occur several years after a severe drought, while depressed maize yields will occur in the same year as a severe drought. Below, we take agave lifetime to be 15 years; if annual rainfall drops below the critical level for agave in any given year, it will affect three cohorts of agave, such that yields for a cohort of agave will be 0 in years 13, 14, and 15 following a severe drought.[2]

[1] This is a stylized assumption; even established agave plants can die in a prolonged drought. But because mature agave can be harvested prior to mortality in a drought year, the main impacts of drought on agave production occur in years subsequent to the drought. Young plants are also more susceptible to drought than are adults (Suzanne Fish 2006, personal communication), so the major production shortfalls will occur after a generation's lag. In contrast, shortfalls in maize production are concurrent with drought. This is the main distinction between agave and maize we are trying to test with these simplified assumptions.

[2] Because many agave produce stalks within the age cohort nearly simultaneously, the window of opportunity for harvest is fairly narrow. Farmers might have achieved adequate buffering by continuously planting agaves or cultivating more than one agave species, employing species that matured at different rates (Wendy Hodgson 2006, personal communication). Our model does not take this complexity into account, but we assume that farmers had some such strategies.

Table 1 Summary of variable definitions, parameter definitions, and default parameter values used in the analysis

Symbol	Definition	Default Value
Variables		
M_t	Total stored maize biomass available in period t	
x_t^j	Agave biomass density (e.g. kg/unit area) in age class j in period t	
r_t	Total rainfall in period t	
Parameters		
$\hat{r}$	Mean rainfall	varies
σ_r	Rainfall standard deviation	varies
Y_{max}	Maximum maize yield	30
$\overline{r}_m$	Rainfall level at which yield reaches its maximum (expressed as a percentage of the mean rainfall)	100
$\underline{r}_m$	Rainfall level below which yield is zero (expressed as a percentage of the mean rainfall)	50
δ_c	Decay rate of maize in storage	0.2
$\underline{r}_j$	Rainfall level below which juvenile agave plants die	30
$\overline{r}_a$	Rainfall level below which the survival of adult agave plants begins to decrease	30
$\overline{s}_j$	Maximum survival rate for juvenile agave plants	1
$\overline{s}_a$	Maximum survival rate for adult agave plants	1
A	Intrinsic growth rate for agave	0.6
U_d	Quantity of food demanded	20
U_m	Quantity of food below which nutritional needs are not being met (used to define a famine event)	15

4. Above a certain (high) annual rainfall, annual growth for both maize and agave is assumed to saturate such that increased rainfall does not lead to increased yield. (We ignore the potential detrimental effects of water-logged soils on both agave and maize.) This saturation point is assumed to be lower for agave than for maize ($\overline{r}_a < \overline{r}_m$ in the formal model, see definitions in Table 1 and Figs. 1 and 2 for a physical interpretation).
5. Maize consumption for subsistence is assumed to be favored over agave consumption. Harvested maize that exceeds demand in a given year can be stored for future consumption (with a certain attrition rate for spoilage). Agave plants are harvested once, when they mature (if needed), which occurs when they reach an age of 15 years. If the agave plant is not harvested at the age of 15, it flowers and its caloric content is lost.

These general characteristics of maize and agave are based on historical and ethnographic accounts of cultivation practices (Castetter *et al*. 1938; Parsons and Parsons 1990; Fish *et al*. 1992). We emphasize that for our purposes, the details are not as important as the fundamental trade-offs associated with each cultigen-longevity, drought-tolerance, and desirability. The qualitative results of our analysis

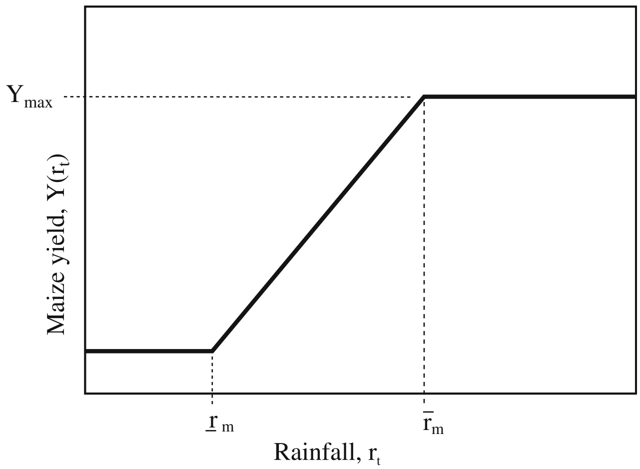

Fig. 1 Depiction of the relationship between crop yield and annual rainfall

concerning under what conditions agave can contribute to reducing famine risk are robust to such details. Our results will depend on the values of the thresholds described above *relative* to one another and *relative* to climatic variables. Given absolute values of such parameters, our results could easily be mapped to actual climatic situations and for particular species choices, but that is not our purpose here. We are interested in the breadth of circumstances under which agave could be potentially valuable for managing risks. Does agave always help, does it help only under a narrow set of circumstances, or does it not help at all? For these questions, the use of relative parameter values is sufficient.

In addition to incorporating these ecological differences in maize and agave production, we incorporate the following features in our model:

1. For simplicity's sake, human population is taken as constant, as is the quantity of maize and agave planted from year to year (planting strategies are not responsive to food stores, recent climatic patterns, or anticipated climatic patterns). While planting is constant, yields of both vary due to rainfall.
2. Since maize is the preferred food source, it is assumed that enough is planted each year to exceed the annual caloric requirements of the population if rainfall conditions are adequate (maximum yields are realized).
3. Although agave is a perennial, each plant is only harvested once when it reaches maturity (in this case, at 15 years). Since maize is the preferred food source, and the establishment of agave can require significant effort, we assume that in any given year the maximum agave yield of those plants that have reached the age of flowering is 100% of the population's annual caloric requirement. This would only occur if each of the previous 14 years had permitted maximum agave survival and growth. The likely yields are below this 100% level, since inadequate rainfall during any year of an agave plant's lifetime can reduce yields.
4. Different rainfall scenarios are considered, ranging from those where average rainfall falls well below that required for maximum maize yields to those where average rainfall exceeds that required for maximum maize yields. Within each average rainfall regime, we also test different scenarios of annual variance in precipitation, from high to low.

With these points above in mind, we now turn our attention to the formal model.

Maize

Because it is harvested annually and can be stored for up to 7 years, our model of maize cultivation generates an annual yield based on annual rainfall (which is stochastic) and, after accounting for what is consumed by the population,

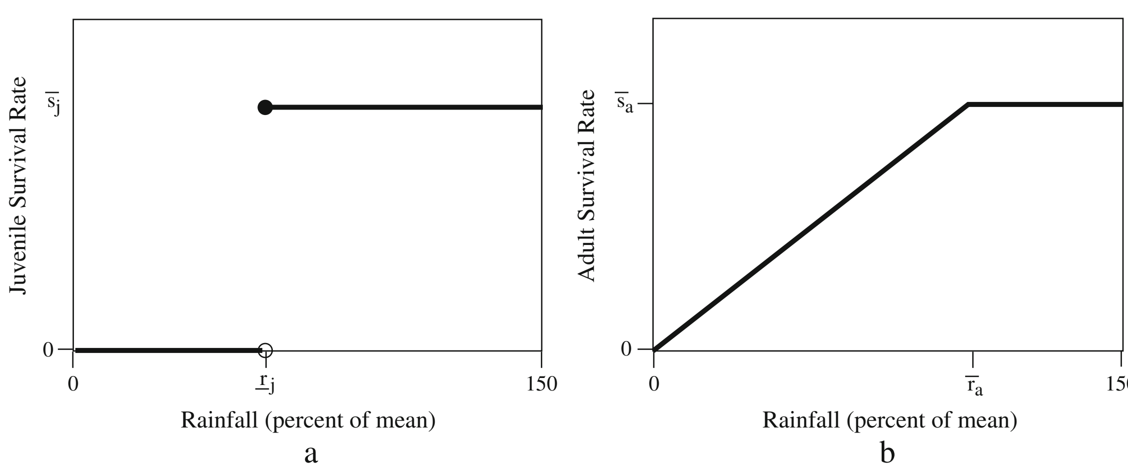

Fig. 2 Depiction of the relationship between agave growth and annual rainfall: **a** juvenile, **b** adult

puts the remainder in storage. Keeping track of total available stored biomass in period t thus requires a single state variable, M_t, which evolves according to the simple discrete stochastic process

$$M_{t+1} = \left(M_t + Y(r_t) - U_t^m\right)(1 - \delta_c) \quad (1)$$

where $Y(r_t)$ is the yield in year t as a function of the random variable r_t—the rainfall in year t, U_t^m is the amount of maize utilized in year t, and δ_c is the decay rate of corn in storage. Equation 1 is interpreted as follows: in each period, if the maize store is sufficient to meet demand, the store is consumed, and the new yield is added. Otherwise, some or all of the new yield is consumed. What remains decays at rate δ_c. Thus, U_t^m is defined as follows:

$$U_t^m = \min(U_d, M_t + Y(r_t)) \quad (2)$$

where U_d is the demand for maize.

The dynamics of the maize store is driven by yields which, in turn, are driven by rainfall. The relationship between yield and rainfall is complex and involves technology, social organization, land resources, topography, etc. Because we are interested in when agave contributes to the capacity of a society to meet its food demands during periods of extended drought, we abstract away from modeling these particulars and focus on only the most general characteristics of maize cultivation. We employ a simple model based on Von Liebig's law of the minimum which states that crop growth is affected by the scarcest nutrient (for us water). Thus, if rainfall is too low, crop yields are zero. At intermediate rainfall levels, yields rise linearly with rainfall. At high levels of rainfall, water is no longer a limiting resource, and additional rainfall no longer has an effect on yields. Figure 1 illustrates this relationship.

Between the upper and lower critical values of rainfall, $\overline{r}_m$ and $\underline{r}_m$, maize yield increases linearly with rainfall. Several different biophysical, social, and technological conditions can be represented by choosing appropriate values for $\overline{r}_m$, $\underline{r}_m$, and $Y_{\max}$. For simplicity, we rescale the random variable for rainfall in terms of a percent of a biologically meaningful benchmark (i.e. the rainfall at which yield reaches a maximum or the mean rainfall for a given representative area). The rationale for assigning values to these parameters is discussed in more detail below.

Agave

Because agave is a perennial plant, age structure is an important determinant of population dynamics. Based on the life history of agave described above, we developed a model with 15 age classes as follows:

$$x_{t+1}^j = s_j\left(r_t, \underline{r}_j, \overline{s}_j\right)x_t^{j-1} \exp\left[a\left(1 - x_t^{j-1}\right)\right] for\, j = 1, 2, 3 \quad (3)$$

$$x_{t+1}^j = s_a(r_t, \overline{r}_a, \overline{s}_a)x_t^{j-1} \exp\left[a\left(1 - x_t^{j-1}\right)\right] for\, j = 4, \ldots, 15 \quad (4)$$

where $s_j(\cdot)$ is the survival of the jth age class from t to $t+1$ (the time unit is years). The splitting of the equations into two groups for j=1,2,3 and j=4,...,15 reflects the fact that young agave plants will not survive periods of extremely low rainfall but well established ones can. The only difference between Eqs. 3 and 4 is in the survival functions, $s_j(\cdot)$ and $s_a(\cdot)$, respectively. In both instances, agave plants in each age class grow according to the discrete logistic, $\exp[a(1-x^{j-1})]$ with intrinsic growth rate a and carrying capacity of 1 biomass unit per unit area. Plants are then graduated into the subsequent age class according to their survival functions. The form of $s_j(\cdot)$ and $s_a(\cdot)$, are illustrated in Fig. 2.

Note that our choice of a carrying capacity of 1 implicitly defines the area and biomass units for agave in relative terms. That is, given a choice for agave biomass units, say tons, the area described by Eqs. 3 and 4 is then exactly that which at carrying capacity will support 1 ton of agave plants. As mentioned above, the actual value of this area is irrelevant to our model as we are assuming that society could cultivate whatever area is necessary to produce a certain biomass. What is important is the biomass a given population unit chooses to plant. As mentioned above, for our base case, we assume the population unit cultivates an area of agave sufficient to meet 100% of its annual caloric needs. The total annual agave production is then defined by the size of the population unit we choose to study. The size of the population unit we choose to study is arbitrary, but for the Monte Carlo simulations we must make a choice. For simplicity and without loss of generality, we chose to study a population unit that requires 20 biomass units of mature agave to meet 100% of the caloric need. A similar argument applies to maize as discussed below.

Figure 2a and b depicts the relationships between $s_j\left(r_t, \underline{r}_j, \overline{s}_j\right)$ and rainfall and $s_a(r_t, \overline{r}_a, \overline{s}_a)$ and rainfall, respectively. If rainfall is below $\underline{r}_j$, the survival rate of juveniles is zero. Above $\underline{r}_j$ the survival rate of juveniles is $\overline{s}_j$, a maximum determined by factors other than rainfall. Because adults can survive periods of low rainfall, their survival rate is positive for all positive rainfall levels. When rainfall is above $\overline{r}_a$, the survival rate is a maximum of $\overline{s}_a$ determined by factors other than rainfall. Below this critical level, adult survival decreases linearly with decreasing rainfall.

Notice that unlike the equation for maize storage, the consumption of agave does not affect the stock of agave plants. Mature agave that is not harvested and instead allowed to flower will die and yield no edible resources to the human population. Clearly, this condition of "use it or lose it" could be a strong disincentive to invest in agave cultivation given that it will only be utilized in some years. On the other hand, if an agave cohort has received sufficient rainfall to allow maximum growth through each of its 15 years, the resultant harvest could meet 100% of the population's annual caloric needs in our model.

Rainfall

The stochastic process defined by Eqs. 1, 3, and 4 transform the stochastic process, r_t into quantities of maize and agave over time. The characteristics of r_t are thus tantamount. For the analysis that follows, we assume simply that

$$r_t = \hat{r}(1 + \sigma_r w_t) \tag{5}$$

where w_t are independent, mean 0, variance 1, normally distributed random variables. Rainfall thus has mean $\hat{r}$ and standard deviation $\hat{r}\sigma_r$. This is a convenient formulation as it allows us to specify mean rainfall and standard deviation as a proportion of the mean. With the model completely specified, we can now determine under what climatic conditions agave significantly contributes to the ability of a population to survive fluctuations in rainfall.

Analysis

As is always the case with stochastic models, it is critical to carefully frame the question to be addressed so that the results are meaningful. Specifically, in the context of our model, what does it mean to say that agave significantly contributes to the ability of a population to survive fluctuations in rainfall? Should this be measured against the number of famine events? Their duration? Their severity? In order to meaningfully address such issues, we computed the frequency of famine events of 1, 2, 3, 4 and greater than or equal to 5 years duration in a 100-year period and examined how the distribution of such events changed under different rainfall scenarios.

The frequencies of famine events were calculated using Monte Carlo simulation. For each scenario, 1,000 runs of 100 years each were simulated. The occurrences of each event type are tabulated and their frequencies computed. The key parameters that were varied in the model were mean and variance of rainfall and whether or not agave was grown. The parameter values used in the model are summarized in Table 1.

The selection of units of measurement is, of course, arbitrary. We have chosen parameters to roughly capture the biology of maize and agave growth, and with ease of exposition in mind. We thus chose to measure rainfall in terms of percentage of a biologically meaningful benchmark as mentioned above. Thus, rainfall of 50 is 50% of this benchmark. Given this choice, we set the parameters governing plant growth as shown in Table 1. For example, a convenient choice for our benchmark rainfall level is that at which maize yield plateaus. We thus set $\overline{r}_m = 100$ and $\underline{r}_m = 50$. Likewise, juvenile agave plants die when rainfall drops below 30, and so on. Our selection of parameters such that both $\overline{r}_a$ and $\underline{r}_j$ are less than $\underline{r}_m$ reflects the fact that agave is more drought tolerant than maize. Because both maize and agave are cultivated plants, their yields depend not only on environmental factors (i.e. rainfall) but also on choices of the cultivators. Specifically, yields depend on the quantity of seeds planted (which implies a certain area) in the case of maize and total area cultivated in the case of agave. Thus, just as with our choice of carrying capacity in the equations that describe agave population dynamics, the choice of $Y_{\max}$ implicitly defines a cultivated area which, in turn, is related to the population unit we wish to study.

Recall that above we chose to study a population unit that required 20 biomass units to meet 100% of its needs. Because maize is the preferred food source and has the potential to be stored, we assume that the population unit cultivates sufficient maize to meet 100% of its caloric needs plus an additional 50% to put into storage. Thus, we set $Y_{\max}$=30 (i.e. 20×150%). With this formulation, we are implicitly assuming a landscape-level production model with a constant annual areas of cultivation for maize and agave.

Parameters that affect human decisions were chosen to reflect specific, and we think reasonable, socioeconomic conditions. The quantity of food demanded, U_d, is set at 67% of the maximum maize yield. This means that when $r_t = 100$, there will be a significant surplus that can be put into storage. Likewise, we set U_m at 15 which is equivalent to 75% of demand. This choice is based on the fact that in societies of interest here, food demand does not significantly exceed subsistence requirements. So that, meeting only 75% of subsistence requirements for one period would have serious nutritional consequences. Consumption at or below U_m for multiple year periods (i.e. 3–5 year droughts) would then almost certainly lead to starvation and death in the absence of migration or alternative sources of food.

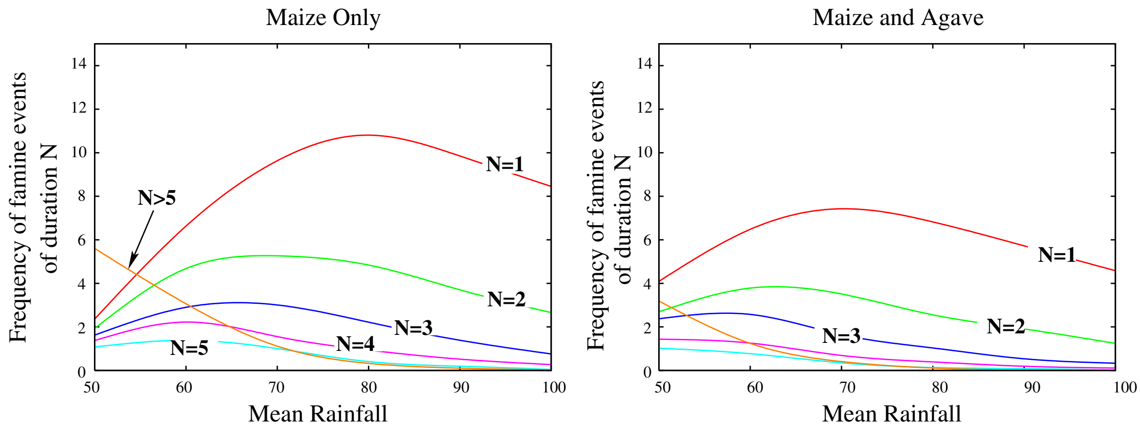

Fig. 3 Frequency of famine events as a function of mean annual rainfall when standard deviation is 50% of the mean. Note that a rainfall level of 100 is the threshold at which maize production reaches maximum yield

The Odds of Starvation

Here we summarize the results of the Monte Carlo simulations for two different levels of rainfall variability: standard deviation of 50% and 20% of the mean, respectively. Figures 3 and 4 show the results of the simulations. The graph on the left in Figs. 3 and 4 shows the frequency of famine events of specific duration when maize cultivation is the sole source of food. The graph on the right is the analogue when agave cultivation is used to complement maize production in times of scarcity. Differences between these curves are a measure of the impact of agave cultivation.

Based on a comparison of these graphs, it is clear that the frequency of famine events of all durations tends to be lower when maize cultivation is complemented with agave cultivation. However, this is not always true, and there are several subtle observations that can be made based on the analysis. First note that in the Maize Only case, as mean rainfall decreases, the frequency of famine events of duration 5 or less first increases as intuition would suggest, but then *decreases*. This is due to the fact that the frequency of famine events of longer than 5 years increases at the expense of shorter famine events. Thus, when mean rainfall is low, if a famine event occurs, it will be of long duration. The addition of agave significantly reduces the frequency of all famine events. Note, however, that when mean rainfall is below 55, 1-, 2-, and 3-year famine events are more frequent than with maize cultivation alone. This is due to the fact that agave cultivation makes shorter famine events more probable at the expense of longer ones.

The effect of agave is much more dramatic when rainfall variability is lower (compare graphs on the right in Figs. 3 and 4). This somewhat counterintuitive result stems from the fact that variability can have both positive and negative effects on production and the nature of the interplay between the growth characteristics of maize and agave as they depend on rainfall. Consider the case when mean rainfall is 100. Because maize production is flat for rainfall above 100, exceptionally wet years do not produce yields above those in average years. However, dry years do cause a drop in production. The overall effect of variability is thus negative. If the mean rainfall is 75, on the other hand, wetter-than-average years do generate increased yields that

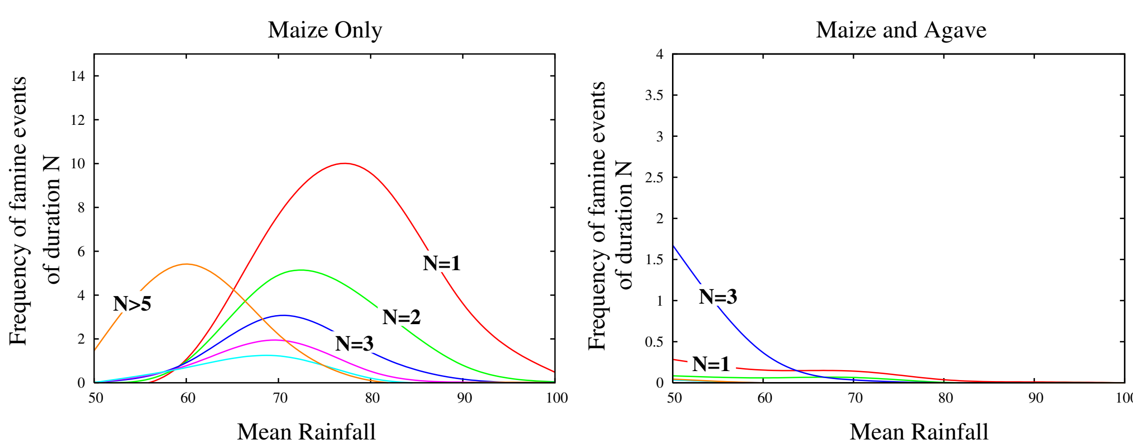

Fig. 4 Frequency of famine events as a function of mean annual rainfall when the standard deviation is 20% of the mean

may offset drier-than-average years. Thus, given sufficient storage capacity, rainfall variability would have little effect on the frequency of famine, even with only maize cultivation. This is evident in the shape of the curves in Fig. 3. Specifically, until mean rainfall drops below 80, the frequency of drought events increases relatively slowly. Thereafter, the frequency of longer drought events ($N>5$) begins to increase sharply, when the negative effects of extra dry years begin to outweigh the positive effects of extra wet years.

Why doesn't the cultivation of agave make more difference in this context? Because when mean rainfall is relatively high, maize cultivation with high rainfall variability combined with storage capacity allows food demand to be met most of the time. In this case, the conditions under which agave would make a difference are extremely rare. When rainfall is relatively low, on the other hand, the occasions when agave would make a difference become more frequent. Unfortunately, more variable rainfall increases the likelihood that the agave crop would be compromised as well. Thus, agave cultivation will not significantly reduce the frequency of famine if rainfall variability is too high.

Under some rainfall regimes, however, agave cultivation can dramatically reduce the frequency of famine events (Fig. 4, right). When the standard deviation is only 20% of the mean, agave cultivation reduces the likelihood of a famine event to nearly zero. The frequency of famine events of all lengths, except $N=3$ fall to less than 1 in 100 years for mean rainfall levels between 50 and 100. When mean rainfall drops below 70, famine events of duration 3 become the most probable due to the life history characteristics of agave in our model: all plants in age classes 1–3 die during an extremely dry year. This single year event will generate a period of 3 years with no agave that will occur 11 years later. This, coupled with a string of years in which maize yields are below subsistence levels that overlap this period will produce a famine of duration 3. However, even if mean rainfall is 50, at the lower bound for maize, such an event will only occur once every 60 years.

Combining the results from the "Maize Only" and "Maize and Agave" simulations, we are in a position to comment on the conditions under which agave cultivation could transform an uninhabitable landscape into an inhabitable one. Specifically, in order for agave to make a difference, the distribution of rainfall must be such that rainfall in a "typical" dry year falls between the minimum requirements for agave and maize (between 30 and 50 in our case, but this result would hold more generally), respectively. To explore the importance of variance in rainfall, we performed an additional set of simulations in which the rainfall level was held constant at 70 (roughly in the center of the linear portion of the maize growth curve) and the standard deviation of rainfall was varied (Fig. 5).

Comparing the Maize Only and Maize and Agave cases highlights the role of variability in the system. It is striking that in this case, variability has little effect on the frequency of famine events in the Maize Only case. This is because a rainfall level of 70 is in the region where the maize growth function is linear. Thus, good years balance bad years, and the number of famine events is driven by storage capacity. Equally striking is the effect of variability on the frequency of famine events for the Maize and Agave case. When the standard deviation falls below 70% of the mean, the frequency of famine events begins to drop markedly, approaching zero when the standard deviation reaches 20% of the mean. The role of "storage" of some sort (physical infrastructure or agave) is highlighted by the differences between these two cases. Obviously when storage is available, it is possible to reduce famine events. However the capacity to do so depends critically on the nature of the infrastructure (i.e. the life history characteristics of agave). Thus, given the mean and standard deviations of rainfall for a given area and the number of

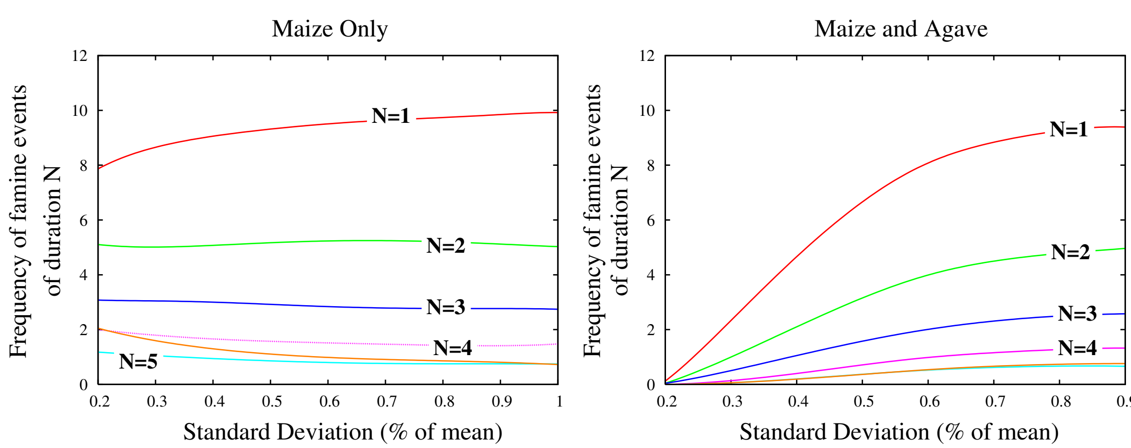

Fig. 5 Frequency of famine events as a function of standard deviation (% of the mean) when mean rainfall is 70

famine events of particular durations a population can tolerate, the model can predict whether agave cultivation can render such a landscape inhabitable. In the case when mean rainfall is 70 and the standard deviation is less than 20% of the mean, agave cultivation transforms an uninhabitable landscape with maize alone into an inhabitable one.

Model Sensitivity and Alternative Strategies

Because they depend on a particular model specification, the question of the generality or robustness of the results discussed above naturally arises. For example, we know that agave makes a significant difference when rainfall variability is low, but when it is high, how does the fact that people may have planted several species of agave with different maturation times affect the results? How does increasing the total area cultivated in agave or the intensity of cultivation of young agave plants affect the results? To explore these questions we ran a series of numerical experiments for the high rainfall variability case. The results pictured in Fig. 6 show the difference between the number of expected famine events in a 100-year period for alternative strategies and the base strategy of planting 20 units (sufficient to meet 100% of food demand) of a single species of agave that has a 15-year life cycle.

The most obvious variable that an agave cultivator would have to contend with is the density of juveniles to plant. There is a limit to how many adult plants a given area can support and this fact is captured in the model. Planting too many juveniles is a waste of effort. However, ethnographic accounts (Zorrilla and Batanero 1988) suggest that agave cultivators knowingly plant more juveniles than a given area can support and allow them to compete. They then select the plants they feel are most likely to survive and cull those they deem less desirable. Thus, eventual output of mature agaves is fairly insensitive to the initial number of juveniles, provided “enough” are planted. The model results bear this fact out. Once x^0 is above the minimum necessary to generate sufficient biomass to meet the carrying capacity at age 15, the model results become completely insensitive to x^0.

Next, the agave cultivator is faced with the question of how much total area and how many different agave species

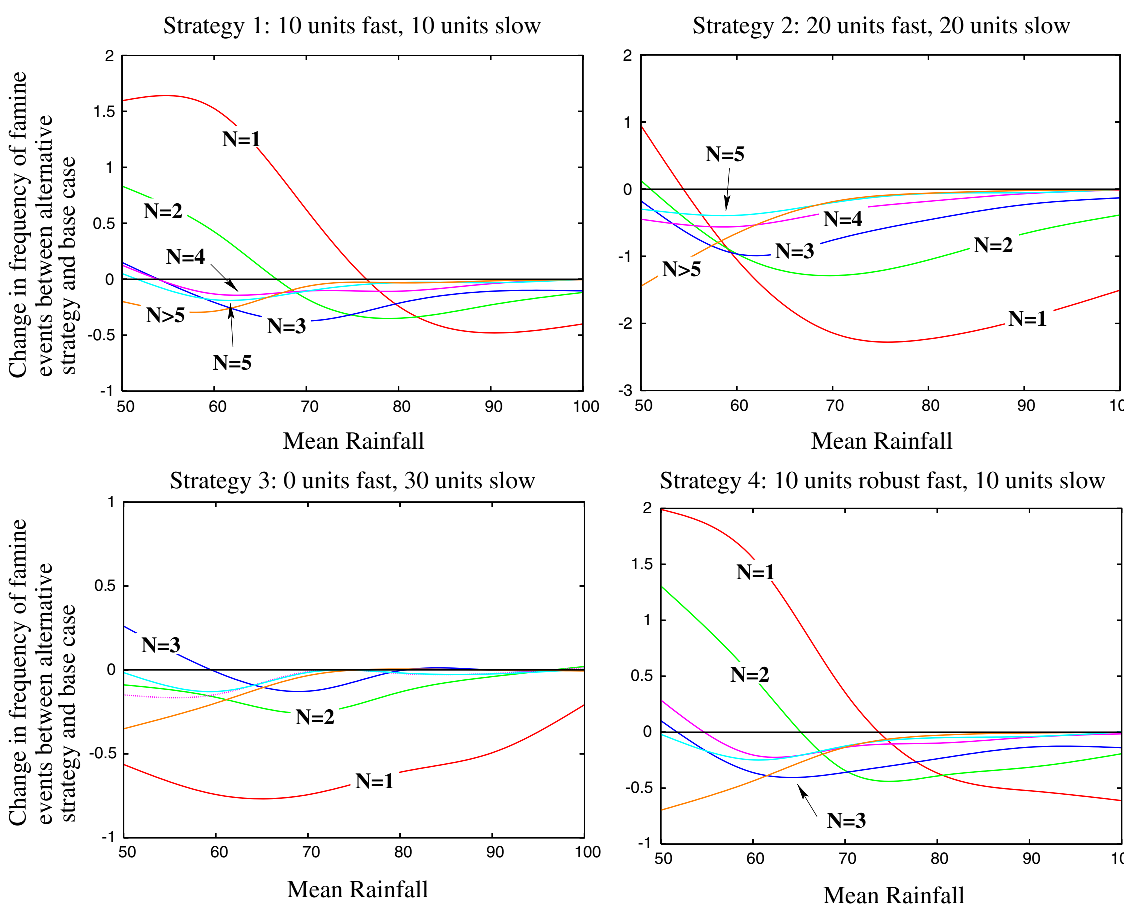

Fig. 6 Performance of alternative strategies versus the base strategy of planting 20 units of agave with a life cycle of 15 years (Fig. 3, right). The *Y*-axis is the difference in the number of famine events for the alternative strategy listed above each graph and the base strategy. A negative value indicates the alternative strategy performs better

to cultivate. In the analysis above, we assumed that sufficient area is planted in a single species to produce enough agave to meet 100% of the population's caloric needs should the maize crop fail (20 area units). It may be better to plant more area in a single species or the same or more area but in multiple species. Planting additional area or managing multiple crops with different life cycles, however, requires significant physical and intellectual effort. Thus, such strategies would have to confer significant benefits before they would be adopted. The analysis summarized in Fig. 6 suggests that the benefits of such strategies are not that significant when compared to the situation when the basic physiology of the plant is well-matched to the environment.

Specifically we compared the performance of four alternatives to the baseline strategy: (1) ten units of slow maturing agave (15-year life cycle) and ten units of fast maturing agave (7-year life cycle, first three age classes still susceptible to drought), (2) 20 units each of slow and fast maturing agave, (3) 30 units of slow maturing agave, and (4) ten units of slow maturing and ten units of a "robust" fast maturing agave (matures in 7 years and only first two age classes are susceptible to drought). Strategies 1 and 4 require the same amount of labor as the baseline while strategies 2 and 3 require 100% and 50% more, respectively. In order to interpret the results shown in Fig. 6, we must distinguish between two types of famine events: (1) a shortfall in maize stocks that occurs in 1 or more of the years in a 3-year period one life cycle after a severe drought that killed juvenile agaves and (2) a shortfall in maize stocks in a year after a moderate drought that reduced the biomass of adult agave plants to a level insufficient to make up the shortfall. The former is more likely to generate longer famine events while the latter is more likely to be associated with shorter famine events.

Figure 6 shows the implications of these different types of famine events for different strategies. First note that planting species with different life cycles necessarily increases the number of years in which a particular species will be unavailable. For example, for a single species that matures in 15 years, a severe drought in year t will be followed by a 3-year period with no mature agave starting at $t+12$. With two species maturing at 7 and 15 years, a severe drought in year t will be followed by a 3-year period with no mature 7-year agave starting in $t+4$ and a 3-year period with no mature 15-year agave starting in $t+12$. Thus, planting N species will generate N such events. However, when 7-year agave is not available, 15-year is. This strategy thus spreads risks temporally. However, the cost of spreading this risk temporally, given the same amount of labor, is the potential for less available biomass during a particular event. For example, a single severe drought event when cultivating 20 units of 15-year agave will result in 3 years of no agave and 12 years of 20 units. A single severe drought when cultivating ten units each of 7- and 15-year agave will result in 3 years with no 7-year and ten units of 15 year and 3 years with ten units of 7-year and no 15-year. This strategy thus converts 3 years of 20 lost units each to 6 years of ten lost units each—the total loss of 60 units is conserved. The effect of this strategy is shown in the upper left graph of Fig. 6 which, when mean rainfall is above approximately 75, can reduce the frequency of famine events somewhat (e.g. when mean rainfall is 100, cultivating both 7- and 15-year agave species reduces famine frequency from roughly 4.5 to 4 per century). In this case, periods when maize availability falls below ten are relatively rare, so having at least ten units of agave on hand is beneficial. However, when the mean falls below 75, one and 2-year famine events become more frequent because now having ten units of agave in hand more frequently isn't sufficient to make up the shortfall in maize. It is better to have 20 units of agave on hand and fewer periods with no mature agave in this case.

The problems generated by this trade-off are easily overcome: just double the area cultivated and plant 20 units each of 15-year and 7-year species as in strategy 2. This strategy almost always performs significantly better than the base case, but requires twice the effort. The question is whether this strategy is the best use of time. For example, strategy 3—cultivating 30 units of only 15-year species—also reduces famine events in most cases, and is simpler to implement. Finally, how important is the plant physiology, i.e. the fact that the first three age classes die during droughts? Given that the 7-year species matures more rapidly, young plants may reach a stage where they can resist drought earlier. Strategy 4 illustrates the impact of a 7-year species for which only the first two age classes die during a severe drought. It does have a greater impact on longer droughts than the standard 7-year species shown in strategy 1. However, it suffers the same trade-off as strategy 1 when mean rainfall is low.

These experiments illustrate that using more complex strategies involving multiple agave species in environments where a single species is ineffective can reduce the number of famine events in some cases. However, the results summarized in Fig. 6 highlight fundamental trade-offs associated with dealing with uncertainty: for a given level of labor, there is a limit to how much the affects of uncertainty can be reduced and there is likely a trade-off between increased robustness for some circumstances and increased vulnerability for others. One fact remains clear: the effect of different strategies is far less marked than the proper matching of plant physiology with environmental conditions. In the right environmental conditions, agave can make a substantial difference (Fig. 4) with relatively little effort. In other environmental conditions, employing a diverse mix of species will not only help much less, but will require significantly more effort.

The discussion above assumes that society can rely on only two types of infrastructure: physical (maize storage) or biophysical (agave) to cope with dry periods. If these are combined with other infrastructure, a wider range of environments can become habitable. Social infrastructure, for example, may allow a population to tolerate a small number of famine events in a 100-year period (i.e., by temporary relocation or trade). In the case discussed above, it is assumed that society can tolerate no such events, and thus standard deviation must be below 20% of the mean. If, for example, social infrastructure allows a population to tolerate 2 1-year, 1 2-year, and 0.5 3-year (or 1 in 200 years) famine events, the population could tolerate standard deviations of 30% of the mean with agave cultivation. Note that without agave, social infrastructure does not improve the situation. There is thus a synergy between agave and social infrastructure that does not exist with maize alone.

Discussion and Conclusions

The analysis of the simple model of maize and agave agroecology has allowed us to isolate very particular conditions, *in relative terms*, under which agave cultivation can significantly reduce the occurrence of famine events. The emphasis on *in relative terms* is critical. We have not attempted to specify a number of important empirical determinants such as local maize yields, soil conditions, slope, hydrology, agave productivity, rainfall patterns and so forth. This lack of empirical grounding of the model might cause one to question the relevance of the results. However, the model does in fact shed useful light because what is important in determining the qualitative dynamics of such a system is not the *absolute values* of parameters, but rather the *relative values* of biologically meaningful parameters and thresholds. The purpose of this kind of model is not to accurately describe or otherwise depict a particular reality; it is rather to explore the fundamental dynamics of a system characteristic of a range of possible realities.

The model provides insight into the magnitude of the impact of agave cultivation under varying environmental conditions and consequently helps us to specify environmental structures in which a mixed annual-perennial cultivation strategy might materially affect survival. These findings are helpful both in estimating the risk buffering that cultivators might achieve in particular circumstances and also in beginning to specify the range of environmental circumstances under which such benefits might accrue. Where rainfall variability was properly matched to the agroecology of maize and agave cultivation, agave cultivation could reduce ancient populations' vulnerability to famine events by dramatically reducing their frequency. Specifically, agave contributes most significantly to the ability of maize farmers to survive droughts when *both* the mean and the variability of rainfall are "intermediate" relative to $\underline{r}_m$, $\overline{r}_m$, and $\underline{r}_j$. Figures 3 and 5 show that when variance is high, regardless of the mean rainfall, agave does not confer significant benefits. In this case it would make more sense for actors to concentrate on mobility strategies. Likewise, Figure 3 shows that when variability is low and mean rainfall high, it may not pay to invest in agave for subsistence, as it is only needed, on average, one year out of a hundred (i.e., if the mean rainfall is above 95, the frequency of drought events per century is below 1). Thus given either the variance or the mean rainfall, there will be a range of means and variances, respectively, where the effect of agave is most pronounced. Figure 4 shows that for a standard deviation of 20% of the mean, agave has a dramatic effect for mean rainfall between 65 and 90. Finally, Figure 6 shows that combining agave species with different life cycles does not significantly improve the effectiveness of agave cultivation outside the environmental range where it performs extremely well. In summary, this analysis helps identify specific environmental circumstances under which it is most likely that agave cultivation could be a strategy to reduce famine risks.

While agave production could have been an effective risk reduction strategy, this analysis does not assert that it necessarily always was. Indeed, the analysis provides a path for discerning when agave was produced for other reasons. When agave was cultivated outside of the range where it was useful for risk reduction, it was likely being used for other purposes including serving households or elites in the creation of social or political capital. It is also true that we have not modeled every other strategy that may have been implemented; for example stressed populations may have fallen back on wild resources, or they may have drawn on social capital to obtain resources from neighbors. Each alternative strategy, however many there may have been, would have had costs and benefits. A model that would account for all possible strategies would be extremely difficult to operationalize or evaluate and, in any case, would beyond the scope of this paper.

The analysis is one step toward understanding historical developments in the northern Mexican region. Archaeologists have long noted a cycle of northward expansion and subsequent southern retraction of the Mesoamerican civilization. Some have asked whether the cycle was driven by imperial conquest (Kelley 1971), wandering colonists (Braniff and Hers 1998) or feudal lord-like actors (Armillas 1964) taking advantage of long-term climatic cycles. Others have suggested scenarios that were less connected with environmental conditions, such as entrepreneurs seeking rare mineral resources (Weigand 1977), or an emergent local elite adopting the political recruiting strategies of their distant neighbors to the south so as to amass population (Trombold 1990; Jiménez-Betts and Darling 2000). A persistent question concerning all of these scenarios is why large concentrations of populations became possible in areas where they did not exist before. Sauer (1963) and Parsons and Parsons (1990) have suggested that agave cultivation created the ecological capital necessary for large groups to cope with shortfalls in maize production and was thus a key part of the explanation. This analysis shows that in a theoretical context in which the only conditions varying were rainfall and the maize-agave mix, agave cultivation can have the kind of strategic impact on famine avoidance that these authors suggest. Knowing this, we can reasonably predict that there were pockets of geographic areas in pre-Hispanic northern Mexico where the rainfall distribution was such that agave could have had a similar impact. The existence of evidence for intensive agave cultivation at pre-Hispanic centers such as La Quemada (Trombold 1985; Nelson 1992; Trombold and Israde-Alcántara 2005) is consistent with such a prediction. Yet, we are still some distance from pinpointing real-world situations with environmental characteristics amenable to agave-based intensification and comparing their distributions to that of the pre-Hispanic centers. To do so, we will need to control for (a) regional and local variation in rainfall, (b) differences between today's environment and that of 500–900 CE, and (c) the impact of other human activities that altered the retention or concentration of rainfall, especially terracing and irrigation.

The analysis also highlights the importance of a number of other questions, such as how the mean and standard deviation of annual rainfall actually vary among different arid locations and how agaves of different species respond to drought, both as juvenile and mature plants. While we expect that agronomists, climatologists, or ecologists may have collected such data, we have been unable to find either a cursory or comprehensive summary of agave mortality or yield patterns under different rainfall regimes in published sources. At the same time, it shows a pressing need for more environmental data from the periods of ancient occupation to evaluate the interplay of social and ecological variables (Turkon 2004; Elliott 2005).

The main finding of the analysis is thus that supplementing maize cultivation with that of agave under particular conditions had the potential to reduce the probability of a pre-Hispanic northern Mexican farming population being forced to migrate due to famine by as much as 95%. This is a powerful demonstration of the ecological principle of resource diversity as a source of subsistence security for human populations. At the same time it helps us understand the importance of social and technological strategies in mediating environmental conditions. Interesting in this light is the finding of diatoms together with agave Phytoliths in the terrace deposits off the southeast edge of La Quemada (Trombold and Israde-Alcántara 2005). If, as the authors suggest, the occurrence of diatoms implies pot irrigation of the agave plants (the terrace area was not reachable by canals), it would appear that the occupants went beyond maintaining a terrace system that managed the distribution of water and sediments. They additionally tended the agave plants (probably the juveniles) by carrying water uphill several hundred meters to make sure that the plants survived. This work would have been done with the knowledge that it might mitigate a famine event several years hence. In conjunction with the present analysis these data suggest that skilled human interventions can have a great effect on reducing famine vulnerability and that interdisciplinary investigations can detect and help understand the behavior of ancient environmental managers.

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