BEYOND WATER HARVESTING: A SOIL HYDROLOGY PERSPECTIVE ON TRADITIONAL SOUTHWESTERN AGRICULTURAL TECHNOLOGY

Steven Dominguez and Kenneth E. Kolm

This article presents a hypothetical, general model that describes the processes involved in one aspect of traditional Southwestern agriculture: the interactions between soil hydrology and farming technology. In conjunction with extensive participation in hand cultivation with Hopi farmers, studies of soil hydrologic processes in Hopi maize fields have identified hydrological processes directly linked to Hopi field location criteria and farming practices. Field location criteria select for locations where soil textures and soil profile heterogeneity control rates of moisture infiltration, as well as loss to runoff, bare soil evaporation, and drainage. Farming practices, including clearing, maintenance, plant spacing, seed depth, and planting pit morphology, operate in conjunction with soil profile attributes to increase the amount of moisture available to plants and the mobility of that moisture. Effects of both soil profile attributes and farming practices are integrated into the discrete soil volume model of hydrologic processes occurring in the basic unit of Hopi farming, the individual plant clump. This information provides basic insights on ways archaeologists might evaluate the productive potentials of soils, the extent of farmable land around prehistoric communities, and the ranges of climate conditions that permit crop growth on that land.

Este artículo presenta un modelo hipotético y general que describe los procesos implicados en un aspecto de la agricultura tradicional del sudoeste: las interacciones entre la hidrología del suelo y la tecnología del cultivo. Conjuntamente con la participación extensiva del cultivo a mano con los granjeros Hopi, los estudios de los procesos hidrológicos del suelo en campos del maíz del Hopi han identificado procesos hidrológicos directamente ligados a los criterios de localización de los campos Hopi y a sus prácticas agrícolas. Los criterios de localización de los campos privilegian texturas del suelo, y donde la heterogeneidad en la textura controla la infiltración del agua, así como la pérdida superficial del agua, la evaporación de los suelos escasos, y drenaje al suelo profundo. Las prácticas agrícolas, incluyendo el mantenimiento, el espaciamiento de la planta, la profundidad de la semilla, y morfología de hoyos de plantación, funcionan conjuntamente con cualidades del perfil del suelo para aumentar la cantidad de humedad disponible para las plantas y la movilidad de esa humedad. Los efectos de los atributos del perfil del suelo y de las prácticas agrícolas se integran en el modelo "discrete soil volume" de los procesos hidrológicos que ocurren en la unidad básica del cultivo Hopi, la parcela. Esta información proporciona ideas nuevas y básicas en las maneras en que los arqueólogos pueden evaluar los potenciales productivos de suelos, la extensión de la tierra arable alrededor de comunidades prehistóricas, y las condiciones del clima que permiten el crecimiento de cosecha en esa tierra.

Following a century of research, one of the most fundamental problems of Southwestern prehistory remains unresolved: the causes of local and regional resettlements by agriculturists (commonly referred to as "Anasazi"), particularly between A.D. 400 and 1400, have yet to be determined. Currently, researchers are seeking to determine the relationships among settlement locations, landscape attributes, climate change, and prehistoric agricultural productivity by determining areas that could be farmed and climatic limits on crop production in this semiarid environment (e.g., Kohler and Carr 1997; Kohler et al. 2000; Pool 2002; Van West 1994). This type of research requires accurate models of agricultural technology and soil moisture balance in order to estimate crop production across a landscape with variable climate conditions.

Bryan (1929), Hack (1942), and others have developed conceptual models describing the geomorphic conditions that promote the influx of water supplementary to direct rainfall into field locations and describe traditional technologies for capturing that water. In recent years the models have been

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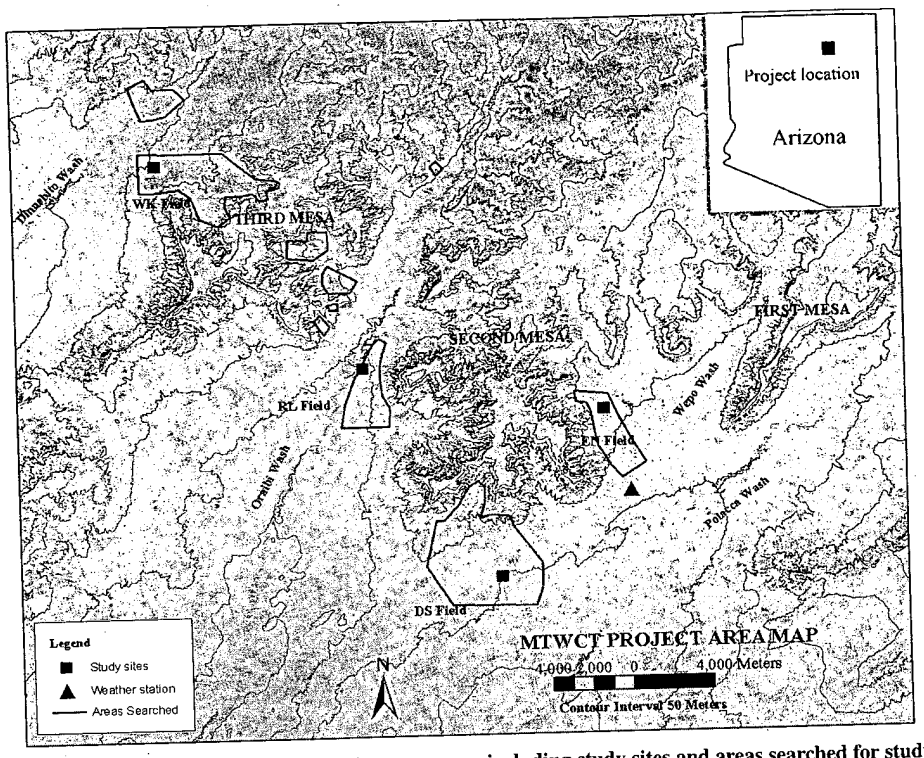


Figure 1. MTWCT project location and project area map, including study sites and areas searched for study sites.

generalized and applied to other geographic and temporal contexts (e.g., Nabhan 1983; Norton 2000). The general characteristics of cultivation practices and aspects of soil profile attributes have also been described for the Southwest (e.g., Bowers 1929; Bradfield 1969, 1971; Muenchrath et al. 2002; Nabhan 1983).

However, much remains to be resolved for analyses of prehistoric agricultural landscapes. With rare exceptions, actual prehistoric and early historic field locations are not known. Little is known about traditional criteria for identifying soils appropriate for agriculture. Although prehistoric farming technologies are commonly hypothesized on the basis of modern Pueblo technologies, such as those of the Hopi, Zuni, and others, the actual technologies used by prehistoric farmers are unknown. Little is known about the interactions between soil hydrology and traditional Southwestern farming technologies that served to increase the reliability of crop production. A general model of hydrologic processes occurring in the soil profiles of fields can help to clarify those issues.

The purpose of this article is to describe a hypothetical, general model that explains the processes involved in the interaction between soil hydrology and farming technology. The article reports a multidisciplinary study of hand-cultivation technology on the Hopi Reservation (Figure 1), the Modeling Traditional Water Control Technology (MTWCT) project. This research integrates anthropological, hydrologic, and geomorphic data into a new perspective on the problem of understanding the functioning of traditional Southwestern agriculture. Consequently, it must accomplish several important tasks.

The first task is to establish the context of the research in archaeologists' current understanding of traditional Southwestern agriculture: that it is a part of a larger strategy of planting in multiple locations to increase the probability of production (Figure 2) and maximizing the quantities of water available to plants. The model operates in conjunction with the diverse technologies for acquiring supplementary water (e.g., Figure 3). It is also necessary to explain that, although it was developed because of observations made at Hopi, the perspective is not to be perceived as a "Hopi model." Rather, the perspective derives from the general framework of soil hydrology and yields general-

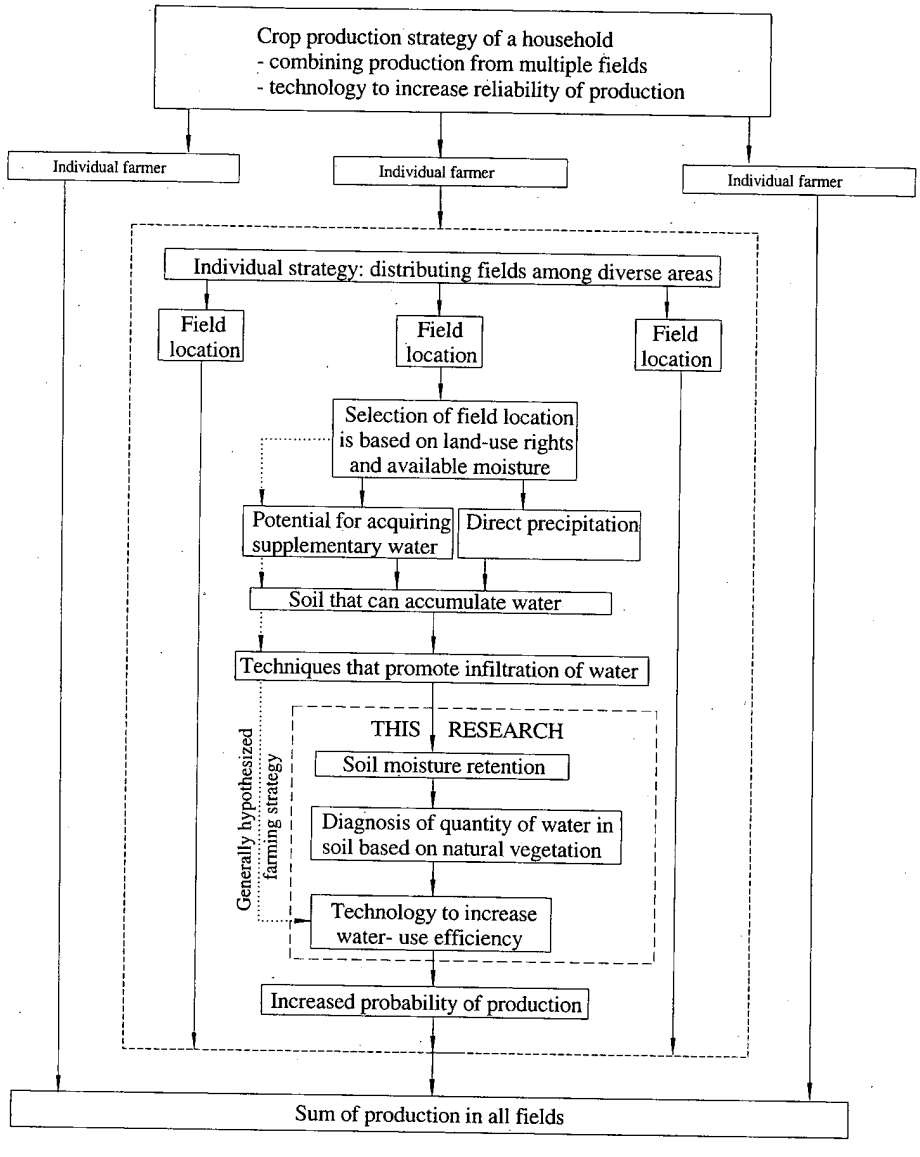


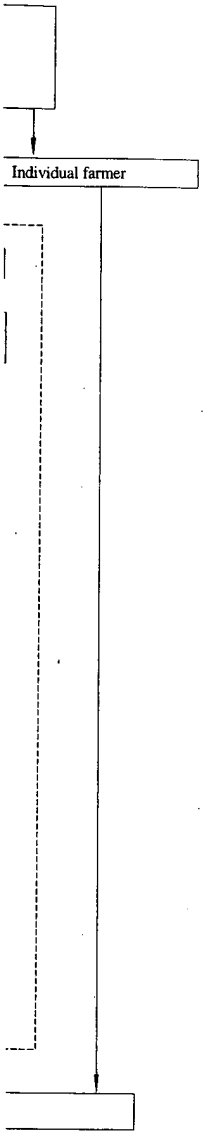
Figure 2. Hypothesized strategies of Southwestern traditional farmers for increasing reliability of crop production.

izations that should prove to be relevant to other traditional Southwestern farming technologies.

The second task is to present soil hydrologic concepts that have been missing from prior discussions of traditional Southwestern farming. The article necessarily defines relevant soil hydrologic and technologic variables necessary for understanding traditional Southwestern agriculture and the effects of climate changes on agricultural production.

The third task is to indicate how the model works. This is accomplished with the example of Hopi farming technology, where relevant processes and interrelationships are recognized. This example incorporates MTWCT project observations with information from prior investigators that is familiar to many readers, but it explicitly interprets the information in the soil hydrologic framework, as well as indicating the consistency among observations. The fourth task is to discuss prospects for use of the perspective in archaeological studies.

In the model, the evaluation of hydrologic processes is facilitated by the widespread Southwestern practice of planting seeds in individual,



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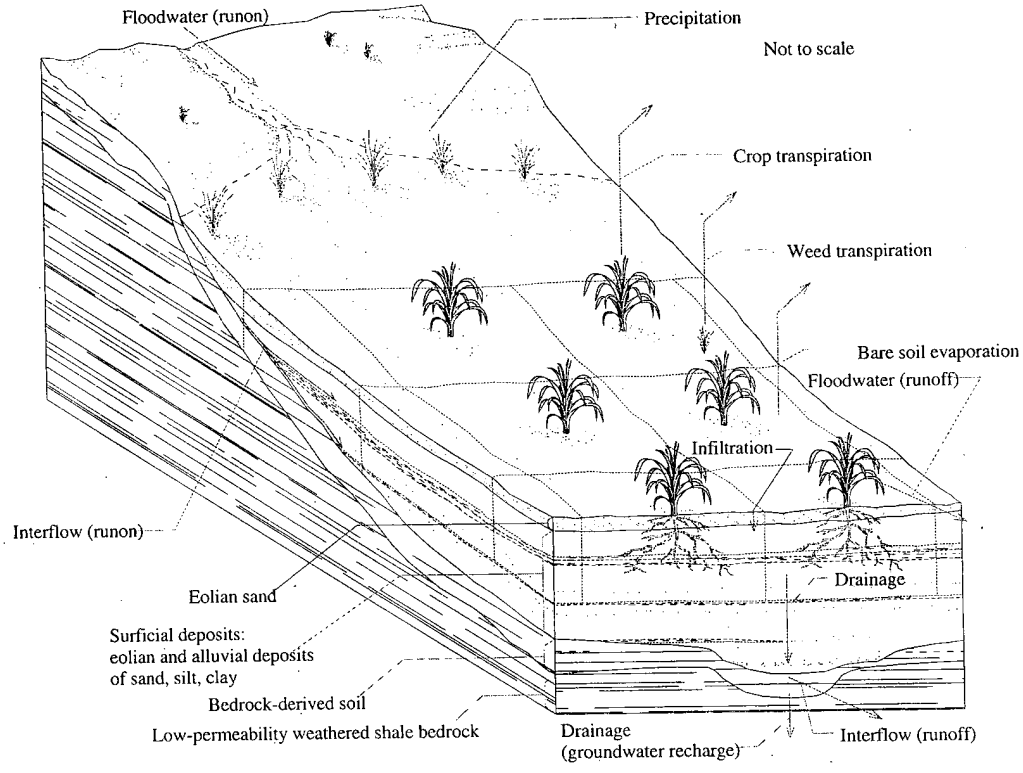

Figure 3. Generalized hydrologic system of ak chin field in Hopi Mesas region.

widely spaced clumps (Figures 3–4). Separated clumps form the basic hydrologic unit for Southwestern farming, a discrete soil volume (DSV) that allows evaluation of moisture balance. Widely spaced plant clumps create a group of reservoirs for soil moisture, each with a volume proportional to the surrounding surface area times the rooting depth. Moisture is exchanged through the surface by processes of infiltration, bare soil evaporation, and transpiration (Figure 3). Moisture is exchanged below the surface by drainage, interflow, matric potential flow, and capillary rise from groundwater (Figure 3). The textures and layering of the soil within a DSV are vital for the retention of sufficiently high quantities of moisture that can be easily extracted by plants. These conditions are best evaluated in the framework of the Soil Moisture Mass Balance Equation (e.g., Hanks 1985), using the principles of soil hydrology (e.g., Jury and Horton 2004; Jury et al. 1991).

Although the model was developed by observing current practices and conditions on the Hopi Reservation, the model should not be perceived as unique to the modern Hopi. It is hoped that identification of the general technologic and soil hydrologic principles involved will promote the development of models and techniques to evaluate the functions and effectiveness of technologies applied in other temporal, climatic, geomorphic, and cultural contexts. At this stage it is difficult to assess the relevance of the proposed model to other contexts, and that is beyond the scope of this article. Dendroclimatological (e.g., Dean 1988) and geomorphic data (e.g., Hack 1942) indicate significant changes in environmental factors that affect crop production since the beginnings of agriculture in the Southwest. Additionally, farmers in other parts of the Southwest occupy climatic and geomorphic contexts that vary in some greater or lesser degree from the environment of the Hopi. However, similar field soil profiles and similar farming practices have been observed in other contexts (e.g., Muenchrath et al. 2002; Nabhan 1983; Sandor et al. 2002), suggesting that generalized Southwestern farming strategies and variants on strategies might be identified and evaluated. A generalized

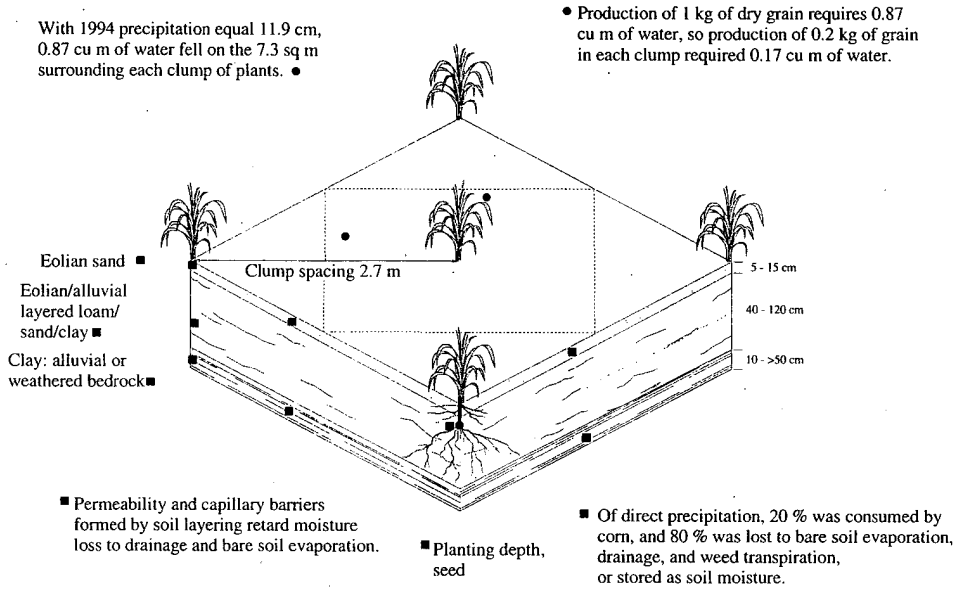

Figure 4. Example of soil moisture balance in the "Discrete Soil Volume," for clumps spaced at 2.7 m (based on Manolescu 1995 data).

model and analytic approach can facilitate evaluation of hypothesized or observed technologies and comparisons among dissimilar spatial and temporal contexts (Maxwell 1995; Rhode 1995).

The ensuing text begins with a consideration of the context of this perspective among other perspectives on the general nature of Hopi and other traditional Southwestern agriculture. That is followed by a description of the environment of the Hopi and the MTWCT project. Subsequent discussions of the moisture requirements of maize and soil hydrologic principles introduce concepts, data, and analytic techniques for evaluating interactions among climate, soil, and technology. These variables are then used to evaluate the hydrologic functions of Hopi farming technology observed by the MTWCT and prior investigators. The article concludes by considering the general nature of Hopi farming and prospects for incorporating the perspective and approach into archaeological research.

Perspectives on Hopi and Other Traditional Southwestern Agriculture

Traditional Southwestern farmers must overcome problems caused by low average precipitation combined with high interannual variability, as well as high potential evapotranspiration (PET: the maximum amount of water that can be removed from a surface by the combined processes of evaporation and plant transpiration) and the lack of irrigation systems. To cope with these problems, Hopi farmers employ a strategy of locating fields in multiple locations, where precipitation and hydrologic characteristics are often dissimilar, so at least one field might produce. In each of those locations, they employ practices that increase the efficiency of water use and to increase the influx of supplementary water if it is available (Figure 2).

The practice of locating fields in widespread areas apparently forms part of a general strategy for decreasing the risk of deficient production in any single field location (e.g., Hack 1942; Hegmon 1989). Because summer storms often cover small areas, a farmer's strategy of planting in widespread locations increases the probability that rain will fall on at least one field. Fields will often occupy catchments in diverse geomorphic settings that will have dissimilar hydrologic responses to precipitation inputs. Overall, the farmers of a household decrease the probability of insufficient production by combining the produce of multiple fields in dissimilar

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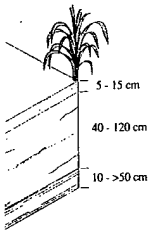

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Farming practices that influence the influx and retention of supplementary water further reduce the risk of insufficient crop production. Supplementary water includes "runon" of any surface or subsurface water from outside of the field (e.g., Figure 3). Hack (1942), Bryan (1929), and many others describe relationships between topography and soil profile attributes that promote the generation of runoff in upslope areas and the influx of that supplementary water from arroyos, hill slopes, and interflow (subsurface flow in saturated conditions) to fields (see Figure 3). Hack's and Bryan's conceptual models have been applied to other geographic and temporal contexts, and the geomorphic and pedologic relationships of hill slope systems that cycle sediments and soil nutrients have been described (e.g., Nabhan 1983; Norton 2000). Clark (1928), Cushing (1920), and others describe farming techniques that improve the infiltration of surface water into soil profiles in fields (Figure 3), including water spreaders, mulching, and other techniques.

There are two kinds of farming practices for making efficient use of water. The first involves selecting locations with soils that accumulate and retain high levels of moisture. The second includes clearing, planting, and maintenance practices that make the best advantage of the moisture stored within the soil.

Some relationships among field location criteria, soil hydrologic processes, and farming practices have been noted. At Hopi, for example, Bowers (1929) has observed the critical role of selecting locations with soil profile attributes that retain water in conjunction with farming techniques that conserve that water. Bradfield (1971) discusses the use of vegetation characteristics by Hopi farmers to identify locations that have higher soil moisture. Muenchrath et al. (2002) mention a Zuni farmer's vegetation criteria for field selection. Investigators at Hopi, including Bradfield (1969, 1971), Clark (1928), Hack (1942), and Prevost et al. (1984), as well as those in other areas, including Russell (1983), Sandor (1995), and Sandor et al. (2002), have noted the function of sand mulch in retarding moisture loss to bare soil evaporation and the function of clay substrate in preventing drainage loss. Statistical tests by Homburg and Sandor (1998) indicate the presence of significantly greater water content in mulched soils. Patterns of association among topographic contexts and geomorphic processes that develop sediment and soil attributes beneficial to soil hydrologic processes in fields are noted by Bradfield (1969, 1971), Nabhan (1983), Norton (1996), Norton et al. (2003), and Sandor et al. (2002). The maintenance of soil profile attributes by eolian and alluvial processes at Hopi locations is noted by Beaglehole (1937) and Forde (1931), and that by alluvial processes at Zuni locations, by Norton (2000), Norton et al. (2003), and Sandor et al. (2002).

Traditional planting and cultivation practices also improve the accessibility of moisture to plants and improve plants' consumption of soil moisture. The advantages of hand tillage over machine tillage in preserving the soil profile and moisture contents have been suggested (e.g., Beaglehole 1937; Bowers 1929; Muenchrath and Salvador 1995; Muenchrath et al. 2002; Prevost et al. 1984; Stewart and Nicholson 1940). The importance of timing planting to correspond with periods of higher soil moisture has been noted by Beaglehole (1937) and Muenchrath et al. (2002). The advantages of placing seed deep in the soil profile are noted by Beaglehole (1937), Manolescu (1995), and Muenchrath et al. (2002). Potential advantages of increased spacing and the resulting lower plant densities are suggested by the data of Manolescu (1995) and Muenchrath et al. (2002). The importance of controlling the depth of planting relative to zones of higher soil moisture during hand planting are suggested by Manolescu (1995) and by Muenchrath and Salvador (1995). The high numbers of seeds planted in each clump probably ensure the germination, emergence, and survival of a sufficient number of plants (Forde 1931; Manolescu 1995; Muenchrath et al. 2002). The high number of plants in each clump appears to afford protection from drying and cutting by strong winds (e.g., Beaglehole 1937; Forde 1931; Underhill 1946). Use of windbreaks in protecting plants from desiccation and cutting (e.g., Bowers 1929) and in soil maintenance has been noted (e.g., Clark 1928). The function of weeding in moisture conservation has also been noted (e.g., Forde 1931; Manolescu 1995; Muenchrath et al. 2002).

The diversity of geomorphic contexts and associated practices that influence the influx and infil-

tration of supplementary water account for much of the observed diversity of Southwestern agricultural technology. In contrast, techniques for increasing water-use efficiency appear to be repeated throughout the Hopi Reservation with limited variation. The same techniques are consistently applied in locations where water is a limiting factor. The techniques are used whether water is derived from direct precipitation alone or from supplemental sources: the techniques are used in rain-fed farming, as well as *ak chin* (arroyo mouth) and other water-harvesting technologies. The techniques appear to be used regardless of crop, climatic context, or prospects for acquiring supplemental water. The exceptions to this occur where supplementary water can be consistently acquired. In these locations the techniques are often modified, especially in spring gardens.

Similarities and contrasts among observations made at Hopi and in other parts of the Southwest suggest a set of strategies common to many areas, as well as a degree of variation that can be explored through engineering studies (as described by Maxwell 1995, 2000). Comparison, contrast, and evaluation of changes in technologies in relation to climatic and geomorphic variation over time or space can be facilitated by the integration of these many observations into a generalized model (Rhode 1995). In the framework of such a model it should be possible to determine soil profile attributes that are advantageous to farming, the geomorphic processes that promote the development of such attributes, means for identifying locations with appropriate soils, and an understanding of how a traditional agricultural technology influences the movement and availability of water in soil that affects potential crop production. The discipline of soil hydrology (e.g., Jury and Horton 2004) provides a physically based framework for such analyses, yielding the means to analyze soil profile attributes for an evaluation of the movement of water into, within, and out of a soil profile.

In recent years, agricultural model development has extended to computer simulations of production, and there are two notable examples. Van West (1994) has used an empirical approach that relates dendroclimate data to potential production by calibrating modern production data. Pool advocates the development of a "means of estimating prehistoric maize production in the past without the need for historic production figures" (2002:5). Pool (2002) used the CERES-Maize 2.1 software (Hoogenboom et al. 1999; Jones and Kiniry 1986) to estimate potential production in the Mimbres Valley considering the technologic attributes of plant and row spacing, seed depth, and planting depth in relation to soil attributes and climate inputs. While these methods are promising, there is still a need to understand the hydrological functioning of prehistoric agricultural technologies and to increase the accuracy of simulation techniques.

The "Modeling Traditional Water Control Technologies: Floodwater and Seepage Fields" Project

The MTWCT project is supported by the National Science Foundation with assistance from the Hopi Water Resources Program and the Hopi Cultural Preservation Office. To date, the MTWCT project has identified study sites, installed electronic monitoring stations, studied the pedology and geomorphology of the sites, participated in hand cultivation activities, and performed preliminary analysis of field data.

The MTWCT project was initiated with the hypotheses that field location would be controlled by geomorphic and topographic attributes that promoted runoff in upslope positions and accumulation of resulting runon in a downslope position. Yet, during the search for suitable study sites, three facts became clear. First, in attempting to identify the surface or subsurface sources for supplementary water in the fields examined, it was observed that not all fields or areas in fields can receive either surface or subsurface runon, due to their relationships to topography. Second, not all areas that can receive runon have soils that are suitable for accumulating and retaining water. Third, Hopi farmers do not necessarily rely on topography alone in choosing a location to farm. Rather, they rely on the density and vigor of key plant taxa that indicate levels of soil moisture. These three observations suggest that there is another set of processes that operate independently of runon. Subsequently, the hypothesis was revised to state that site selection is based primarily on soil profile attributes that increase moisture input and storage (as indicated by key plant taxa) and, secondarily, on the availability of supplementary water.

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In order to develop a model relating traditional Southwestern agriculture to soil hydrologic processes, the MTWCT project focuses on the impact of hand tillage and hand planting on water balance, and fields with these two characteristics were sought in the initial search for study sites. Although hand-planting techniques are still used by many farmers, many locations are now plowed rather than hand tilled. The search for completely hand-cultivated fields included major field concentrations, from areas west of Third Mesa to areas east of Second Mesa (Figure 1). Due to the current frequency of machine cultivation, only six completely hand-cultivated fields were located during the initial search, all in areas south and east of Second Mesa. Two farmers gave consent to study their hand-cultivated fields, the EN and the DS fields (Figure 1).

The EN field is an *ak chin* field, with a catchment area of 30.4 ha and field area of .4 ha on an alluvial fan of approximately 1.0 ha. Soil in the catchment consists primarily of Sheppard-Monue Complex (Sheppard series are mixed, mesic Typic Torripsamments; and Monue are coarse-loamy, mixed, mesic Typic Camborthids), with inclusions of Jeddito loamy sand (coarse-loamy, mixed [calcareous], mesic Typic Torriorthents) and Cannonville clay loam (clayey, montmorillonitic [calcareous], mesic, shallow Ustic Torriorthents; National Resource Conservation Service [NRCS] 1996). EN estimates that the arroyo flows as often as twice per year, but it can be two years between flows. The DS field covers an area of .6 ha. One-fourth of the DS field receives floodwater one to three times a year from a contributing area of .8 ha, while three-fourths of the field can be classified as a "sand dune" field. The field lies within a Jeddito loamy sand map unit (NRCS 1996).

At each site, the catchment of the field (defined as the entire area that could possibly drain to the field) was identified by topographic map and field inspection, as were the primary geomorphic units, associated soils, and relationships to vegetation distributions. The sedimentology and pedology of these geomorphic units were characterized by excavation of profile pits on differing slope positions and geomorphic contexts, both within and outside of fields. Pits within fields were limited to one or two to minimize damage to fields. Pits were dug to weathered bedrock or to a maximum of 2.2 m. Profile attributes were recorded using the guidelines of Birkeland et al. (1991), including field assessment of soil textures. Soil samples were collected for evaluation of gravimetric soil moisture, texture, and soil nutrients and submitted to the Soil, Water, and Plant Testing Laboratory at Colorado State University. Comparisons among a sample of profiles, two recorded outside of the EN field and one recorded within the field, are presented in subsequent text.

A major component of MTWCT research is acquiring instruction and participating in hand-clearing, planting, and maintenance techniques and the resulting struggle to raise a crop. Two Hopi farmers participated in the excavation of soil profile pits and the evaluation of profiles. This provided an opportunity to compare the farmers' perspectives and direct observations of the interplay between the applied technology and soil conditions.

In the MTWCT analytic framework, components of the Soil Moisture Mass Balance Equation (e.g., Hanks 1985), soil profile characteristics, and the hydrologic processes involved in moisture gain and loss in soils are evaluated using vadose-zone hydrologic models (e.g., Richards 1931; Stormont and Anderson 1999; Stormont and Morris 1998; Van Genuchten 1980). In this framework, it is possible to derive models of soil moisture mass balance and equations for describing the movement and distribution of water in homogeneous soils and layered soils. Data from climate and soil moisture modeling are used to further refine the model and will be reported in future publications.

Unfortunately, the three years of MTWCT fieldwork fell within an extended severe drought. In all three years, crops grew in only four to ten fields on the *entire reservation*, and damage by animals was extensive. For these reasons, plant growth and grain production data for these two years are extremely limited, so Manolescu's (1995) production data are used in this text.

Environment of the Hopi Mesas

The project area, the central Hopi Reservation, lies at the south edge of Black Mesa, at elevations between 1,520 and 1,890 m. The climate is semi-arid to arid, with cool winters and dry springs. Summers are hot, and precipitation can vary greatly throughout the year (Table 1). Precipitation

Table 1. Annual and Monthly Precipitation at Keams Canyon, in cm (WRCC 2004).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
mean	1.85	2.03	3.25	1.63	1.04	.69	3.51	4.11	2.54	2.72	2.03	2.59	27.99
2 years in 10 will have													
≤	.43	.84	.61	.41	.25	.15	1.12	1.60	1.50	.81	.69	.74	
≥	3.23	3.30	5.49	2.92	2.01	1.57	5.46	6.50	4.19	4.60	3.28	4.09	

recorded at Keams Canyon in the east end of the reservation is limited (Western Regional Climate Center 2004), with an average annual precipitation of 28 cm (Table 1). On average, a total of 14.5 cm of precipitation falls during the growing season, between April and September. However, the growing season begins during the period of lowest precipitation, from April to June. It is therefore advantageous for farmers to locate fields on soils that can retain a large portion of the 13.5 cm that fall between October and March. Based on exponential distribution analysis (Haan 1977:99) of hourly precipitation records from Keams Canyon (NCDC 2004) for the period 1982 to 1994, storm events in April to September have an average intensity of .32 cm/hr and length of .71 hr, giving a mean precipitation magnitude of .23 cm per event. Relative humidity recorded by the MTWCT climate station is low, with readings generally below 10 percent, and estimated potential evapotranspiration can be as high as 1.2 cm/day. The high PET rate is often exacerbated by high winds, especially in spring.

Black Mesa is a large cuesta that dips to the southwest. Bedrock exposed at the south edge includes the Wepo, Mesa Verde (Toreva Member), Mancos, Dakota, Cow Springs, Entrada, and Carmel formations. These are the upper sequence in a complex intertonguing of layered mudstone, siltstone, sandstone, and coal lenses that form the Black Mesa hydrologic basin (Cooley et al. 1969). The dip of the sedimentary units varies greatly, with higher units dipping to the south and east and lower units dipping to the north and east (Cooley et al. 1969; Lopes and Hoffman 1977: figs. 1, 3). Severe deformation in bedrock is absent (Cooley et al. 1969). The south end of Black Mesa is dissected by drainages that run northeast to southwest, forming a series of parallel ridges and canyons. The Hopi Mesas are remnants of Toreva Formation at the south ends of the ridges.

The sequence from Wepo Formation to Carmel Formation includes units with lenses of sandstone that act as aquifers (sufficiently permeable to allow the accumulation and flow of water): the Upper Toreva, Lower Toreva, Dakota, Cowsprings, and Navajo formations (Cooley et al. 1969). The sequence also includes units with lenses of mudstone and siltstone that act as confining units (impermeable, prevent drainage of water to lower units, and permit accumulation of water near their upper boundaries): the Wepo, Middle Toreva, Mancos Shale, Entrada, and Carmel formations (Cooley et al. 1969). While groundwater provides most domestic water, it serves a much smaller role in agriculture. The large, continuous aquifer formed by the Dakota and Cow Springs formations dips to the north, and discharge from this aquifer is rare. The higher bedrock systems are greatly dissected, and aquifer systems that discharge near the Hopi mesas are small and discontinuous. Springs are common along exposures of the Wepo/Upper Toreva contact, the Upper Toreva/Middle Toreva contact, and the Lower Toreva/Mancos Formation contact. These units provide water for domestic purposes and spring gardens (e.g., Hack 1942). Although alluvial aquifers occur in the lower reaches of the major drainages, Dinnebito, Oraibi, Wepo, and Polacca, surface flow in most reaches is intermittent, and these drainages do not provide consistent or predictable sources of water for agriculture (e.g., Gregory 1916; Hack 1942).

Sand and clay in bedrock and in surficial deposits constitute sources for alluvial and eolian sediments that are layered with highly contrasting textures. The parent material of most National Resource Conservation Service (1996) soil units on the Hopi Reservation is alluvial and/or eolian sediment overlying dissected shale or sandstone (Cooley et al. 1969; NRCS 1996). A large percentage of the fields is located on soils formed in stratified sediments deposited over Mancos Shale bedrock: 28 percent are in Jocity series units; 17 percent, in Jeddito fine sandy loam; 11 percent, in Tewa very fine sandy

loam; 5 percent, in Wepo clay loam; and 5 percent, in Ives fine sandy loam, which is formed in nonstratified sand on floodplains (compiled from Hopi Land Information Office and NRCS [1996] data). The remaining 34 percent of fields are distributed among other stratified and nonstratified soil units.

Vegetation in the central part of the Hopi Reservation includes shrubland, woodland, grassland, and very limited riparian habitats. Soils derived from eolian and alluvial deposits generally support shrub and grassland and include most agricultural fields (compiled from NRCS 1996). These soils are well suited to growing wild herbaceous plants and shrubs, including sand sagebrush (*Artemesia filifolia*), Cutler Mormon tea (*Ephedra cutleri*), big sagebrush (*Artemesia tridentata* var. *wyomensis*), shadscale (*Atriplex confertifolia*), winterfat (*Krascheninnikovia lanata*), fourwing saltbush (*Atriplex canescens*), needle-and-thread (*Hesperostipa comata*), ricegrass (*Achnatherum hymenoides*), blue grama (*Bouteloua gracilis*), and galleta (*Pleuraphis jamesii*; compiled from NRCS 1996). Scattered Utah juniper (*Juniperus osteosperma*) and pinyon (*Pinus edulus*) occur, but this group of soils is poorly suited to the production of coniferous trees (compiled from NRCS 1996). Soils derived from mixed colluvium and alluvium are moderately suited to growing wild herbaceous plants and shrubs. Many areas are well suited to the production of Utah juniper and pinyon, with canopy cover up to 35 percent. The nonarboreal taxa resemble those occurring in eolian and alluvial soils (compiled from NRCS 1996). Soils derived from thin eolian and alluvial deposits over sandstone are moderately suited to the production of wild herbaceous plants and shrubs. These soils can be moderately suited to production of Utah juniper and pinyon, with canopy densities also up to 35 percent (compiled from NRCS 1996). Nonarboreal taxa include Cutler Mormon tea, big sagebrush, sand sagebrush, Bigelow sagebrush (*Artemesia bigelovii*), Stansbury cliffrose (*Purshia stansburiana*), needle-and-thread, blue grama, ricegrass, galleta, and others (compiled from NRCS 1996). These soils are commonly associated with the mesa tops and edges.

Moisture Requirements of Maize

Maize consumptive requirements are often stated as a precipitation equivalent, a depth that is the sum of antecedent soil moisture storage and depths of precipitation, runon, and irrigation that must be present throughout the growing season. For example, Shaw (1988:611) states that maize requires a minimum summer rainfall of 15 cm without irrigation and is grown in areas where annual precipitation ranges from 25 to >500 cm. Precipitation depths are not easily used in the estimation of potential production, because the relationship between precipitation and crop production is affected by the quantities of water retained in the soil, the cultivar, planting and subsequent care of crops, and plant density (e.g., Arnon 1975).

The use of water use efficiency (WUE) values (Gardner et al. 1985) makes it possible to use plant densities as a variable in estimating potential production. This is the volume of water required to produce a given weight of dry matter. Data on the WUE of maize are available for a limited range of Midwestern varieties of maize but provide a general guideline. Midwestern maize requires approximately 390 g (390 cc) of water for every 1 g of dry matter produced above ground, regardless of climatic conditions (Gardner et al. 1985:95). Consequently, production of 1 kg of dry matter requires .39 m^3 of water. The harvest index (HI; Ritchie et al. 1992) is the percentage of dry matter that is grain, when necessary conditions for growth are met. The HI for Midwestern varieties of maize is approximately 45 percent (Ritchie et al. 1992), and production of 1 kg of grain requires .87 m^3 of water. As an example, production of .2 kg of grain would require approximately .2 kg/.45 kg/kg = .44 kg of total dry matter production. The water consumed would be approximately 390 cc of water/g of dry matter x 440 g = 172,000 cc = .17 m^3 of water.

The WUE and HI set upper limits on the production of dry matter and grain with a given volume of water available to plants. The actual quantity produced is contingent on initial soil moisture stored, the timing of precipitation, the specific cultivar, and crop maintenance. To reach this upper limit, sufficient water must be available at critical times, especially during seedling establishment, pollination, and filling of grain (e.g., Ritchie et al. 1992). Therefore, sufficient water must be stored in the soil, or else precipitation and/or supplemental water must be available at the right times. At Hopi and many other locations in the Southwest, the acquisition of supplemental water is dependent

on precipitation near fields. While precipitation cannot be controlled, it is possible for the farmer to influence the volumes of soil moisture reservoirs and the exchange of water into and out of reservoirs through choice of location and technological attributes.

Soil Hydrology and Agriculture

This section provides a limited review of relevant soil hydrology principles. The concepts presented form a preliminary basis for developing techniques to analyze soil/technology interactions and provide the foundation upon which the discrete soil volume model was developed.

In order to increase the total volume of water available to plants, an agricultural technology in an arid- or semiarid land must serve both to decrease the loss of water and to increase input, whenever possible (Hillel 1972). Consequently, one goal of Southwestern archaeologists and agronomists must be to evaluate interactions between farming techniques and soils that operate to serve those purposes in potential field locations or remains of agricultural features. The application of the concepts and estimation techniques of soil (vadose-zone) hydrology facilitate such evaluations. Soil profile attributes and the hydraulic characteristics of component materials set known limits on the volume of water that can be stored within a profile and the rates of water movement in and out of the profile, as well as determining the depths where most water will be stored. Complementing information from soil profile attributes, the descriptions of a farming technology provide specifications for plant spacing, planting depth, and other practices. Using the concepts and estimation techniques of soil hydrology, it is then possible to evaluate interactions between soil and technology for a range of technologic and soil profile specifications.

Soil Profile Attributes and Soil Hydrology

Generalized soil profiles, such as those given by NRCS, and other soil classifications give clues regarding the hydrological operation of soils and their prospects for supporting farming. A soil map unit description specifies a soil profile that has a high probability of being found within the boundaries of the map unit. The soil moisture regime of a classification (e.g., Buol et al. 1994) gives the seasonal distribution and levels of moisture required to develop a particular classification. Additional information includes soil depth, available water capacity, and general engineering and agricultural capacities.

However, soil classifications can only give general guidelines for evaluating agricultural hydrology for several reasons. First, a soil map unit description is a generalized profile ("pedon") that is much more variable than suggested by its description. The degree of variability is emphasized by landscape context descriptions and the soil unit inclusions listed for individual map units. Second, the soil hydrologic profile is distinct from the pedologic profile (Dingman 1994). Pedologic horizons are distinguished by the proportion of organic material present and the degree to which materials have been removed (eluviated) or deposited (illuviated) by chemical and physical processes within the profile (Dingman 1994). Horizon development is influenced by hydrologic and related processes acting over time. However, evaluation of soil hydrologic processes requires means to evaluate the movement of water in observed strata, particularly when considering the minimally developed soils (Entisols and Inceptisols) that are commonly found in agricultural fields of the Southwest or when considering soils of relict landforms or humanly modified locations.

In contrast to the pedologic profile, the soil hydrologic profile is divided into regions that are defined by the movement of water. In Figure 2, the saturated zone extends downward from the top surface of the groundwater zone. The vadose (unsaturated) zone extends upward from the top surface of the groundwater zone. It includes the surface soil, the root zone, the intermediate zone (where roots do not extend), and the tension saturated zone immediately above the groundwater zone (saturated by capillary rise of water in the soil). The extent of each zone can vary greatly over short distances on the topography and rapidly through time. They may or may not correspond to pedologic horizons. Consequently, in evaluating the hydrologic functioning of soils, archaeologists and agronomists not only must evaluate how representative the soil profile attributes provided by classifications are but must complement the information from soil classifications with an evaluation of the hydrologic profile.

Table 2. Maximum Per-Plant Dry Matter and Grain Production by Plant Spacing in Rainfed Fields with 10 cm of Precipitation (Using the WUE for Midwestern Varieties Provided by Gardner et al. 1985).

Plants /ha	Mean spacing (m)	Mean surface area (m^2)	Volume of water from 10 cm precip. only (m^3)	Maximum dry matter production (kg)	Maximum grain production (kg)
60,000	.41	.17	.02	.05	.02
10,000	1.0	1.0	.1	.3	.1
5,000	1.4	2.0	.2	.5	.2

Soil Moisture Reservoir and Soil Moisture Balance

The reservoir concept of hydrology considers any compartment or volume of air, soil, or rock to be a potential reservoir for water (Dingman 1994). This is also true for voids in bedrock and soil, as well as irregularities on the earth's surface (such as depressions, drainages, or dams). Each volume has the ability to hold a greater or lesser quantity of water when filled. In any volume of soil, the total quantity of water stored at any point in time is equal to the initial quantity of water, plus all water added through direct precipitation and runon (both surface and subsurface flow), minus all water lost to runoff (both surface and subsurface flow), drainage, bare soil evaporation, and plant transpiration (see Figures 2 and 4).

Agronomic data (e.g., Arnon 1975; Norwood 2000; Ritchie et al. 1992) indicate the importance of plant spacing in the growth of dry matter and grain. This is primarily due to the surface area of soil that can absorb water from precipitation or surface runon for each plant or plant clump and the volume of the soil reservoir from which plants can extract moisture and nutrients. The area of soil around each clump of plants forms a "microcatchment." When plants are very widely spaced, the microcatchment extends as far as the plant roots can extract water. As spacing decreases below that maximum distance, plants begin to compete with one another for water and receive decreasing quantities of water. Eventually, the roots of individual plants or clumps begin to occupy the same soil volume and directly compete for water and nutrients. Consequently, there is a direct relationship between spacing and the quantity of water that can be extracted by each plant or clump.

For modern row cropping in semiarid environments, plant densities of 10,000 to >60,000 plants/ha are common (e.g., Norwood 2000, 2001). The average soil surface area surrounding each plant ranges from 1.0 to .17 m^2, and average spacing is 1.0 to .48 m (Table 2). By contrast, Hopis use much greater spacing. For example, the average spacing of plant clumps recorded in 2003 in sample transects in the EN field is 2.8 m, the average surface area per clump is 7.8 m^2, and the average number of plants per clump is four. This gives an average surface area per plant of 2.0 m^2 and an average spacing of 1.4 m (Table 2).

The maximum volume of water that each individual plant or clump could receive from direct precipitation alone, without lateral movement of water into the DSV, is equal to the surrounding soil surface area (A) times depth of precipitation (P). The same principle applies to water derived from surface runon or irrigation. Depending on the soil hydraulic characteristics, the total volume actually infiltrated into and retained in the soil can be much less than the total volume of direct rainfall, as discussed later. The volume of water from precipitation can be estimated for individual storm events or for longer periods. For agricultural estimates, it is useful to consider the period from the end of the growing season of one year to the end of the following growing season. This covers both the period of moisture recharge, when crops are not consuming water, and the period of consumption. If a location were to receive a total annual precipitation of 10 cm and no supplemental water, plants at an average spacing of 1.4 m could each receive a maximum of .2 m^3 of water (Table 2). More closely spaced plants would receive correspondingly smaller volumes of water (Table 2). If all of the precipitation was retained in the root zone and was available to plants, and no other supplemental water was received, the maximum quantity of dry matter

that could be produced by a plant in a field with a specified plant density can be estimated as $DM_{max} = AP_d/.39$ (at 1 kg of dry matter per .39 m^3 of water). If plants are spaced at an average of 1.4 m, the maximum mass of dry matter produced by each would be DM_{max} = .5 kg, and the maximum quantity of grain produced (at .45 kg of grain per 1 kg of dry matter) would be G_{max} = .2 kg. The maximum production of more closely spaced plants would be smaller (Table 2).

To evaluate the suitability of a soil moisture reservoir for farming, it is necessary to consider additionally whether the soil can hold the quantities of water introduced by a single event or over the course of a year. In conjunction with soil depth (b) and porosity (φ), the surface area created by clump or plant spacing defines the potential moisture storage volume: $V_v = Ab\varphi$. Soil depths vary greatly, but we can assume that the majority of the rooting zone is the upper 1.8 m of the soil (this is true for Midwestern varieties of maize but is unknown for Southwestern varieties). Based on this assumed rooting depth, the volume of the soil around a plant or a clump is $V = Ab_r$. Sand has an average porosity of .43 cm^3/cm^3. For silt, φ = .46 cm^3/cm^3, and for clay, φ = .38 cm^3/cm^3 (Carsel and Parrish 1988). As an example, then, the maximum volume of water that could be held within the upper rooting zone of a homogeneous silt with a plant spacing of 1.4 m is $V_v = V\varphi$ = 1.66 m^3, that is, the volume of voids in that volume of soil. The total void volume not only may be controlled by hypothesized plant spacing, rooting depth, and soil porosity but may additionally be limited by depth to bedrock and the volume of clasts greater than 2 mm (Rawls et al. 1993).

The total void volume, as defined by plant spacing, potential rooting depth, and soil porosity, is, then, the discrete soil volume that provides a preliminary basis for estimating the maximum quantity of water available to a plant with a given precipitation amount. With sufficient plant spacing and moisture retention, even small quantities of direct precipitation can provide sufficient moisture, and, in some locations, supplementary water becomes available. However, it is also necessary to consider how much direct precipitation can be infiltrated during water-input events, as well as how much water is retained and is available for the plants. It is likely that most will be infiltrated into the soil surface, while some can be lost as runoff. Further, it is likely that the remainder of the moisture is lost to the processes of weed transpiration, bare soil evaporation, and drainage or might remain in storage. The first process is controlled by the weeding practices of the Hopi, while the last three are largely controlled by attributes of the soil profile and the hydraulic characteristics of the component materials in the field locations chosen by the farmer.

Soil Hydraulic Characteristics

Soil hydraulic characteristics and heterogeneities determine the retention of moisture and the rates of movement into, within, and out of any volume of soil (e.g., Jury and Horton 2004; Jury et al. 1991; Stormont and Morris 1998). These characteristics not only define locations and the effectiveness of drainage barriers and mulching but also limit the rates at which roots can extract water. The hydraulic characteristics of soil can be estimated and primarily vary with respect to soil texture. This is due to the pore sizes of the texture classes and consequent capillarity (Jury and Horton 2004; Jury et al. 1991). Textures at the extreme ends of the soil triangle, sand, silt, and clay, behave in distinctively different manners. Moisture retention and mobility are affected to a lesser degree by pore morphology, organic content, bulk density, structure, inclusions, vapor exchange, and hysteresis (the lag in soil wetting and drying in small pore spaces). Soil texture exerts the strongest control over moisture relationships (Jury and Horton 2004; Jury et al. 1991). For this reason the effects of soil textures are emphasized in this discussion.

In soil hydrology, there are three primary variables to be considered along with porosity: volumetric soil moisture, hydraulic conductivity, and head (energy state). The energy state, called hydraulic head or h, is the summation of forces acting on water in the soil, the primary forces being soil matric potential (forces due to capillarity), gravity (measured by height above a reference point), and adsorption of water to soil particles (Jury and Horton 2004; Jury et al. 1991). Head is commonly expressed in pressure units such as kilopascals or in length units such as centimeters. Head is negative pressure, the suction imposed against such forces as gravity and evaporation. At saturation, h is equal to 0 cm, and the negative value increases

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as soil dries. While values of head can be >–100,000 cm, the maximum value that is usually considered in soils is –15,000 cm, which is assumed to be the "permanent wilting point" (PWP; Jury and Horton 2004; Jury et al. 1991). At $h = -15{,}000$ cm plants can extract very little water from the soil. Several commonly used soil hydraulic characteristics are defined on the basis of hydraulic head. "Field capacity" (FC) is the volumetric soil moisture remaining in most soils after draining for two–three days. After that period, downward movement of water in most soils becomes negligible. FC is generally calculated at a matric potential of –340 cm (Jury and Horton 2004; Jury et al. 1991). As used in this text, plant-available water, PAW_h, is the quantity of water that is removed from a soil as it dries from a specified value of h to PWP. As used by NRCS, available water capacity (AWC) is a specific value of PAW_h, the quantity of water that is extracted from a soil between FC and PWP (in centimeter of water per centimeter of soil). The effects of water stress on plant processes become apparent at a head of approximately –2,000 cm (Gardner et al. 1985: tab. 4.1), and in subsequent text this value is used in the evaluation of soil/water/plant interactions. Similar to temperature, head tends to equilibrate (Jury et al. 1991), and given appropriate conditions, a single value of h can come to exist throughout a soil profile.

Volumetric soil moisture (θ) is measured as the quantity of water in a vertical column, generally measured as vertical centimeter of water per vertical centimeter of soil. The maximum quantity a soil can hold at saturation is equal to the soil porosity, the total volume of the voids per unit of volume. Porosity ranges from .35 for coarse sand and gravel to .50 for some clays. The minimum, or residual water, is the quantity held at large values of matric potential (>–15,000 cm) by the adsorptive force of the solids and varies from .045 for sand to .095 for clay loam (Carsel and Parrish 1988), primarily as a function of the fraction of clay present (Jury and Horton 2004; Jury et al. 1991). The quantity of water that remains in soil between the extreme values of h, from saturation to residual water, is called $\theta(h)$ and is largely controlled by texture (Jury and Horton 2004; Jury et al. 1991). Hydraulic conductivity, $K(h)$, is the rate that water can travel in a soil at a given condition of head or volumetric soil moisture and is measured as distance per unit of time (e.g., cm/hr or cm/day). Hydraulic conductivity is greatest when a soil is at saturation. This quantity is called K_{sat}, and average values range from 713 cm/day for sand to <.5 cm/day for clay (Carsel and Parrish 1988). As negative values of head increase and levels of moisture decrease, the rate of water movement, $K(h)$, decreases. The variation of $K(h)$ with respect to h and θ is largely controlled by soil texture (Jury and Horton 2004; Jury et al. 1991).

Values of h, θ, and K_h are mathematically related (e.g., Brooks and Corey 1964; Clapp and Hornberger 1978). Perhaps the equations most commonly used in the United States are those of Van Genuchten (1980; see Appendix A). The relationship between head, h, and volumetric soil moisture, $\theta(h)$, is generally called the moisture characteristic curve (MCC). The MCC for any soil is the graph of values for $\theta(h)$ estimated and graphed with respect to h, using Van Genuchten's equation for $\theta(h)$ and the hydraulic parameters for the particular soil (Carsel and Parrish 1988). Figure 5 shows the MCCs for the primary particle classes of the soil triangle, sand, silt, and clay. Examination of MCCs helps to understand how AWC and PAW relate to soil texture and why plants can easily extract water from one soil texture but not from another. The relationship between hydraulic conductivity and hydraulic head is $K(h)$. $K(h)$ for any soil can be represented as the graph of values for K estimated with respect to h (Figure 6), using Van Genuchten's (1980) equation and the hydraulic parameters for the particular soil (Carsel and Parrish 1988; see Appendix A).

At saturation the volumetric moisture of sand is .43 cm/cm. As shown in Figure 5, sand rapidly loses moisture as head increases: 50 percent of the water that is held at saturation is lost by the time the value of h increases to –10 cm, and 89 percent of that water is lost when the sand reaches field capacity. The AWC of sand is consequently very low: from $h = -340$ cm to $h = -15{,}000$ cm sand releases only $5.5(10^{-4})$ cm/cm of water (Figure 5). Further, the graph of $K(h)$, hydraulic conductivity with respect to head (Figure 6), shows an additional characteristic of sand that is a detriment in some contexts and a benefit in others. Although the average saturated hydraulic conductivity of sand is very high ($K_{sat} = 713$ cm/day), $K(h)$ declines rapidly to .78 cm/day at $h - 20$ cm and to $8.9(10^{-9})$ cm/day at $h - 340$ cm. Due to the high value of K_{sat} in sand,

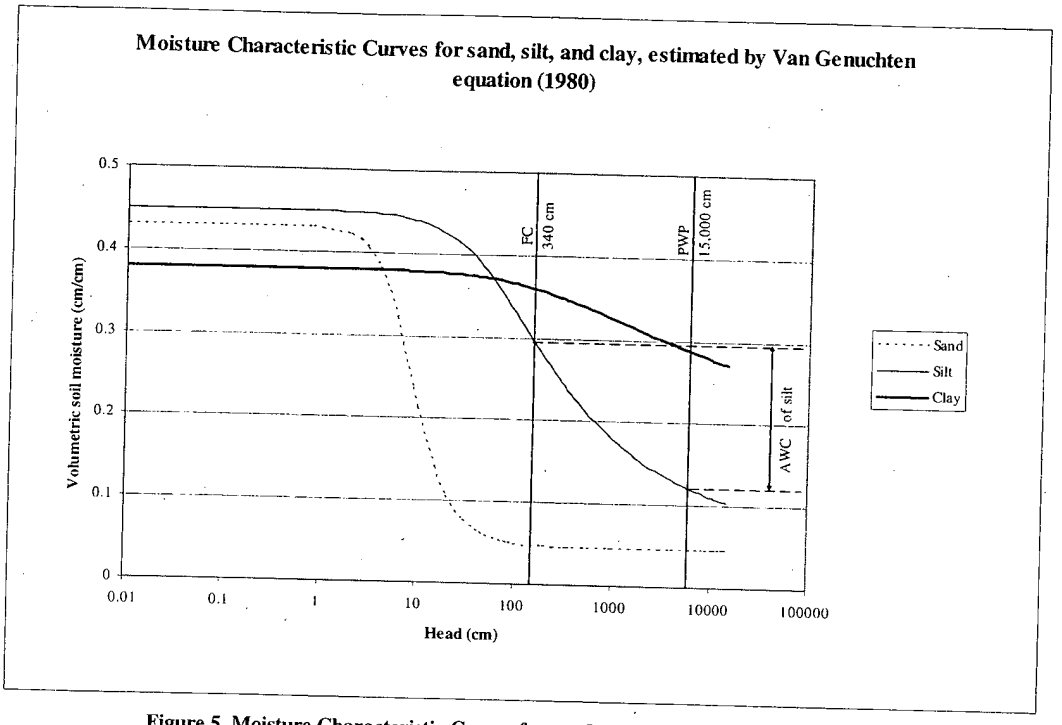

Figure 5. Moisture Characteristic Curves for sand, silt, and clay, in absolute values.

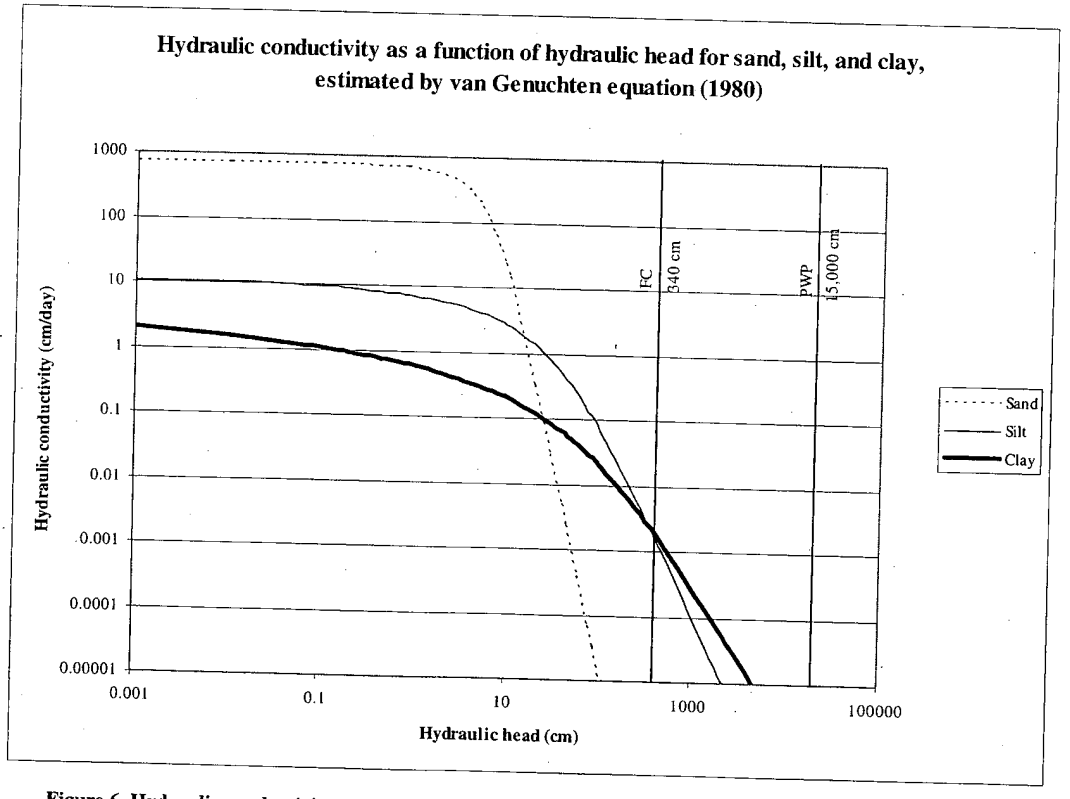

Figure 6. Hydraulic conductivity as a function of hydraulic head, for sand, silt, and clay, in absolute values.

water inputs can be infiltrated rapidly. However, water also drains rapidly out of sand, and the remaining water loses its mobility at low values of h. As a consequence, a profile consisting only of deep sand drains quickly. Water quickly becomes nonconductive, and roots can extract little water. A soil consisting of homogeneous sand performs poorly as an agricultural soil, and one or more layers of a finer texture must be present to prevent drainage loss.

The volumetric moisture of clay is .38 cm/cm at saturation. As shown in Figure 5, clay releases water slowly as it dries and hydraulic head increases. Clay loses .03 cm/cm or 8 percent of the water from saturation to FC and .08 cm/cm or 21 percent of the water from FC to PWP. Relatively little of the water in clay can be extracted by plants: clay releases only .11 cm/cm of water from saturation to PWP. The hydraulic conductivity of clay declines slowly as hydraulic head increases (Figure 6). However, conductivities are overall low, where K_{sat} = .5 cm/day for clay soil with <60 percent clay fraction (Carsel and Parrish 1988) and as low as .02 cm/day for soils with higher clay fractions (Shaw 1994). A profile consisting of only clay will not rapidly lose water to drainage, but plants can extract little water from it. Additionally, infiltration during water input is slow, so water is often lost to runoff. Due to the slow infiltration and redistribution into lower portions of the profile, water remains near the surface and available to bare soil evaporation.

The hydraulic characteristics of silt fall between those of sand and clay (Figures 5–6), and soils with high percentages of silt have good qualities for agriculture. At saturation, the volumetric moisture of silt is high, .45 cm/cm. A large quantity of water is available for plants to extract from saturation to FC, .21 cm/cm. A moderate quantity is available throughout much of the range from 0 to –340 cm. The value for the saturated hydraulic conductivity of silt lies between that of sand and clay, 10 cm/day. $K(h)$ of silt decreases to a level similar to that of clay, .003 cm/day, when hydraulic head increases to 340 cm or FC. It decreases to a much lower value, $3(10^{-8})$ cm/day, when hydraulic head increases to PWP, but the rate remains higher than that for sand. Consequently, in a profile consisting of silt only, a large quantity of water is available for plant extraction. Unlike sand, silt will not drain excessively, but, in time, it can lose a significant quantity through drainage unless a layer of another texture class is present in the rooting zone.

Silt can infiltrate and redistribute a moderate quantity of water during input events, and runoff loss is lower than with clay. However, due to high moisture retention, a large quantity of water can remain near the surface, available to loss by bare soil evaporation. These facts indicate some of the relative advantages and disadvantages of the three primary classes of soil particles, as well as the disadvantages of profiles consisting of only one texture class. The following section considers some of the advantages of the layering observed in the soils of agricultural fields.

Soil Profile Attributes

Alternating coarse and fine layers create a series of permeability and capillary barriers that reduce loss to drainage. A permeability barrier consists of a layer of a material with very low hydraulic conductivity that impedes the movement of water through it. As previously stated, saturated hydraulic conductivity for clay can range from >.5 to <.02 cm/day (Carsel and Parrish 1988; Shaw 1994). The quantity of water that would drain through a clay layer over a 180-day period (e.g., over the cold season period of soil moisture recharge) can range from 3.6 to 90 cm, if the profile remained at saturation. In drier conditions (larger values of hydraulic head), the quantity drained would be much less.

However, it is unlikely that drainage loss would be as great as that estimated with the values of K_{sat} in a soil profile that is layered with strongly contrasting soil textures. This is due to the formation of a capillary barrier at a boundary where a layer of finer soil overlies a layer of coarser soil. Water is held against the forces of both gravity and the matric potential gradient across the capillary boundary. In such an arrangement, the coarse material cannot extract water from the fine soil until the water content of the fine material reaches a critical level that is near saturation. This critical level is determined by the "breakthrough head" (h_w^*) of the coarse material (Stormont and Morris 1998). Water within the coarse materials will be nonconductive, even at low values of hydraulic head (e.g., the low conductivity for sand at 10 cm of head in Figure 6). Water cannot move into the coarse mate-

rial until a sufficient quantity of water is available in the adjacent fine material to raise the water content of the boundary of the coarse material sufficiently to make flow possible at h_w^*. This forms an equilibrium condition where water can be held from drainage as long as no additional water is introduced. When more water is introduced into the fine layer, the additional water will leak through the barrier. The maximum quantity of water that would be held in the fine soil at equilibrium is determined by the soil's MCC at hydraulic head below the breakthrough head. The quantity of water held in such a column (*SC*) is estimated by the equation

$$SC = \int^b \theta\,(z + h_w^*)dz$$

(Stormont and Morris 1998: eq. 8), where b = the thickness of the layer, and θ is integrated from $z = hw^*$ to $hw^* + b$.

Estimated by this equation, the quantity of water that a 50-cm-thick layer of clay can hold above a layer of medium sand with a breakthrough head of 11.4 cm (Baker and Hillel 1990) is 19.5 cm, 2.1 cm greater than the quantity held by a clay layer at FC without a capillary barrier. A 50-cm-thick layer of silt over fine sand can hold 20.8 cm of water, 8.9 cm greater than the quantity that can be held at FC by silt without a capillary barrier. The maximum quantity of additional water that can be held in a soil profile with a series of capillary barriers is dependent on the evenness of the stratum boundary and is equal to the summation of additional water held in each of the layers plus the water held in the coarse material. An example of such an estimate is given in the subsequent section on soil profile attributes in Hopi agricultural fields.

The rate of moisture loss to bare soil evaporation is largely dependent on the texture of the soil at the surface. As noted before, both silt and clay drain slowly and hold large amounts of water throughout the MCC (Figure 5). When silt or clay is exposed at the surface of a profile, a substantial quantity of water is held near the surface, available for bare soil evaporation. The moisture also remains relatively conductive through a wide range of hydraulic head values (see Figure 6), so that more water can be pulled from lower levels of the soil. By contrast, sand drains quickly, losing most of the water at low levels of head, and the water quickly becomes nonconductive (Figure 6). In this condition, minimal water can be pulled to the surface for bare soil evaporation, and the rapidly drained water can become held in the series of drainage barriers in the lower part of the profile. The boundary between the sand and finer material additionally forms an "inverted" capillary barrier to the transmission of water to the surface. Hence, both sand and gravel mulches decrease the loss of water.

In order for plants to extract sufficient water from the soil, the water must be conductive. This condition can be maintained by two factors. First, drainage barriers keep higher levels of moisture in the profile, and water is more conductive in all soils in conditions of higher moisture and lower hydraulic head (Figure 6). Second, silts and loams hold greater quantities of water, and moisture is conductive over a wider range of moisture and hydraulic head values than in sand and clay (see Figures 5–6). Silt and loam layers in the "midsoil" of a soil profile provide a medium that permits more rapid root extraction of water than sand and clay layers do. This is particularly important with the wide spacing of plant clumps, where water flows down the matric potential gradient, "pulled" from the surrounding soil.

Consequently, alternating layers of clays, silts, and sand provide a series of permeability and capillary barriers that reduce the loss of water to drainage and bare soil evaporation. Water drains quickly through a topsoil of sand, and the small quantity of water remaining becomes nearly immobile. A "midsoil" with silt and loam layers retains higher levels of moisture that is conductive over a wide range of hydraulic head values. These conditions are favorable to plant growth. In conjunction with prospects for harvesting supplementary water, these soil attributes are responsible for the distribution of arable land at Hopi.

While these conceptual and mathematical models demonstrate the processes occurring in soils, analyses of actual profile moisture content must derive from repetitive solution of the Richards (1931) equation for transient flow in unsaturated porous media, that is, time-series simulations of moisture input and loss in a specified soil profile. Currently, models are being developed in the Danish Hydrologic Institute *Mike/SHE* software for time-series analyses and will result in future publications contrasting the moisture retention of soil

profiles recorded both inside and outside of agricultural fields.

Soil Hydrology and Hopi Agriculture

Archaeological data suggest that the period of development of agricultural technology in the area around the Hopi mesas may be 2,600 years (e.g., Powell 1983) or more. Presumably, the traditional technology observed today resulted from many years of trial and error. As Whiting (1936) has observed, each newly cleared area and the suite of plants sown are regarded as an experiment: Hopi farmers commonly try one or several cultigens in new locations, retaining successful combinations of crops, locations, and techniques and abandoning those that produce poorly. Experimentation creates a population of farming techniques that are subjected to selection by their relative successes.

Bowers has noted that the skill in Hopi farming lies in the ability to "select locations where the soil retains longest the surface water and to use methods whereby it is retained therein" (1929:455). It is suggested that all phases of current traditional Hopi agricultural technology, including site selection, clearing and tillage, planting, weed control, and maintenance of windbreaks, serve to increase the total volume of water available to individual plant clumps. To evaluate this statement, generalizations regarding the selection of field locations and cultivation practices are examined. The generalizations yield a set of specifications for the soil moisture reservoirs formed. By examining the soil hydrologic processes that occur in the specified moisture reservoirs, it is then possible to determine the interactions among soil profile attributes, technology, and climate. Integration with archaeologists' views on prehistoric agroecology will undoubtedly require further data and debate.

Hopi farmers believe that conscientious application of their farming principles is essential to successful farming, and one farmer stated that "a good farmer can grow more in a poor field than a poor farmer can produce in a good field." Although traditions of agricultural labor input, sharing, and control over climatic events are complex issues that only Hopis can describe, the hydrological principles of traditional farming can be briefly stated: (1) traditional Hopi farmers choose a soil with profile attributes that promote water accumulation and retention; (2) Hopi cultivation practices serve to maintain or enhance the profile while eliminating weed transpiration loss; (3) the planting technique places seeds into a soil stratum with a high moisture level; and (4) spacing of plant clumps creates a microcatchment for each clump that can provide sufficient water with normal precipitation amounts, while runon increases production. The following text describes how Hopi agricultural techniques serve to locate, maintain, and effectively use good agricultural soils.

Site Selection

Evidence collected by the MTWCT project suggests that site selection is based primarily on soil profile attributes that decrease losses to soil drainage and bare soil evaporation (as indicated by key plant taxa) and, secondarily, on the availability of supplementary water. This does not dispute the important role of supplementary water in production, as emphasized by Manolescu's (1995:27) data from 1994. Supplementary water in floodwater fields doubled production, with an average of 283 kg/ha (252 lb/ac; $N = 12$) in fields with floodwater sources and 147 kg/ha (131 lb/ac; $N = 22$) in fields that received only direct precipitation (by Manolescu's assessment).

However, the prospect for harvesting supplementary water is not the sole criterion for field placement, because (1) not all locations that can receive supplementary water, for example, that lie in a drainage or ak chin, will be farmed; and (2) many fields or parts of fields lie on interfluves and drainage divides that cannot receive supplementary water (other than windblown snow). Farmers' statements, field observations, aerial photos, and geographic information system data indicate that not all farmed areas can receive floodwater or interflow. Hack (1942:26) states that 27 percent of the fields are dry farmed, while Manolescu's (1995) data suggest 65 percent. Additionally, Hopi farmers' assessments of the frequencies of flow in drainages that provide supplementary water to their fields range from twice per year to once every four years. Consequently, many floodwater fields must operate without supplementary water for extended periods of time. These facts indicate that selection of field location is not based solely on topographic context and that there are controls over field placement that are more fundamental than potentials for water harvesting.

Figure 7. Dense and vigorous rabbitbrush and ricegrass indicating good soil moisture conditions. Shot E/NE with village of Hotevilla on scarp in background. (MTWCT02/04/04/009)

Based on informants' assessments of the agricultural potentials of unfarmed locations near Second and Third Mesa, field site selection appears to be based primarily on the density and vigor of key plant taxa (especially rabbitbrush, fourwing saltbush, Mormon tea, and ricegrass) that indicate good soil moisture input and retention (consistent with Bradfield 1971), regardless of the source of the water. Topographic context is secondary. For example, a location on an interfluve with a dense, vigorous stand of the key taxa would be chosen over a drainage or alluvial fan lacking key taxa (e.g., "It doesn't have the right bushes. It's too sagey" [too much *Artemisia*]). The density and vigor of other taxa, such as grama and wheatgrass, are sometimes used as a guide. Dense, vigorous stands of nonnative Russian thistle also indicate locations of higher moisture conditions that could be farmed. Some farmers regard natural vegetative taxa to be keys to the *type* of crop that will be favored by a soil. Rabbitbrush and fourwing saltbush indicate good conditions for corn; ricegrass, for beans and corn; and Mormon tea, for watermelon, beans, and corn. Greasewood can additionally indicate good conditions for corn.

The density and vigor of key taxa indicate the degree of moisture and presence or absence of attributes that accumulate or retain water. Figure 7 shows a dense and vigorous stand of rabbitbrush and ricegrass southwest of Hotevilla. These conditions exist both in the shallow drainage to the south (right) and on the interfluve in the north (left) part of the photograph. Both settings are deemed good for planting. The plants indicate that soil moisture is higher than in surrounding areas, whether supplementary water is available or not. After selecting such a location, the farmer replaces the natural vegetation with a crop. The fact that a large percentage of fields are located in drainages and fan deposits results not only from the fact they can

receive supplementary water but additionally from the fact that sequential fluvial and eolian deposition events in those settings can develop layered and moderately deep soil profiles that favor water retention and promote dense, vigorous plant growth.

Hopi farmers emphasize the importance of having sandy layers (*tuuwa*) at the soil surface that act as mulch and clayey to silty layers (*nayavu*) lower in the profile that limit drainage loss (consistent with Clark 1928:235 and Bradfield 1971:17). The emphasis on such layering is consistent with vadose-zone hydrological principles for moisture retention. The alternation of very fine with coarse layers creates a series of permeability and capillary barriers that retard the vertical movement and loss of moisture. It is likely that the field selection criteria described above select for soils that serve those functions, as suggested by a comparison of the profiles recorded inside and outside of the EN field.

Figures 8a–8b show examples of two profiles recorded outside of the EN field that contrast strongly with Figure 8c, the profile recorded within the field. The EN2 profile (Figure 8a) was recorded in the catchment of the EN field, in an eolian deposit on the shoulder of an interfluve, at a point 645 m west and upslope from the EN field. Small and sparse rabbitbrush, gray Mormon tea, snakeweed, grama, and ricegrass are present around the profile pit. The NRCS soil map unit is Sheppard sand, formed in a parent material of eolian sand. The eolian deposit is at least 115 cm deep and resembles Sheppard sand. Little differentiation was observed in the profile, with an A horizon from 0 to 10 cm consisting of sand and Bk horizons from 22 to >155 cm consisting of sand. Roots are dense (less than ten roots of any thickness per 10 cm^2 of exposed profile) to common (ten to two per 10 cm^2) to a depth of 55 cm and rare (~one per 10 cm^2) below.

The profile in Figure 8b was recorded on an interfluve within the catchment, 745 m west and upslope from the EN field. Small and sparse rabbitbrush, gray Mormon tea, snakeweed, grama, and ricegrass are present around the profile pit. The soil is similar to Cannonville clay loam and is an inclusion within the Sheppard-Monue Complex. The parent material is a residuum of weathered shale bedrock. Little differentiation was observed, with an A horizon from 0 to 30 cm consisting of silty clay loam and a C horizon from 30 to 60 cm consisting of clay with residual shale bedrock bedding. Roots are dense to a depth of 30 cm and rare below.

The profile excavated in the EN field is shown in Figure 8c. Vegetation at the edges of the EN field includes stands of dense and vigorous rabbitbrush, Mormon tea, grama, and ricegrass. The field occupies the proximal end of an alluvial fan and can be classified as an *ak chin* field. The soil is similar to Jeddito loamy sand, consisting of stratified alluvial sediments of highly contrasting textures. Due to the presence of Pueblo II ceramics on the surface, as well as the presence of concentrations of Pueblo II ceramics nearby, it is likely that the existing surface of the field was cultivated in the past as well as today. Due to the high degree of differentiation of sediments and lack of correspondence with criteria for A horizon assignment, no horizons were designated. Figure 8c indicates the presence of strata of sand and loamy sand interbedded with strata of silt to clay. In May 2002 roots were observed to be common to a depth of 67 cm and rare to 84 cm. The potential rooting depth may extend deeper than that observed, due to root growth of the maize present in the field. It is assumed to extend to 80 cm.

Layering similar to that in the EN field was observed in each of the six profiles recorded in other agricultural fields. All have at least one layer of clay, silty clay, silty clay loam, silt loam, or other fine-textured soil interbedded with sand to loamy sand. Among the profiles, stratum thickness varies from 2 cm to greater than 50 cm, and there is variation in the spacing between strata and depth below the surface. It is not possible to determine whether all Hopi fields have similar layering, but the common association of fields with soils developed on sediments stratified with particle classes of contrasting hydraulic characteristics suggests their importance in crop production.

The soil/water relations of a soil profile can be evaluated with graphs that show moisture content and conductivity by depth for specified values of matric potential that are assumed to be at equilibration. For each of the three profiles, Figure 8 shows estimates of PAW_h and $K(h)$ by depth at three specified values of matric potential: 0 cm (saturation), –340 cm (FC), and –2,000 cm (initial stages of water stress). The values are plotted by depth, with capillary barrier storage estimated with

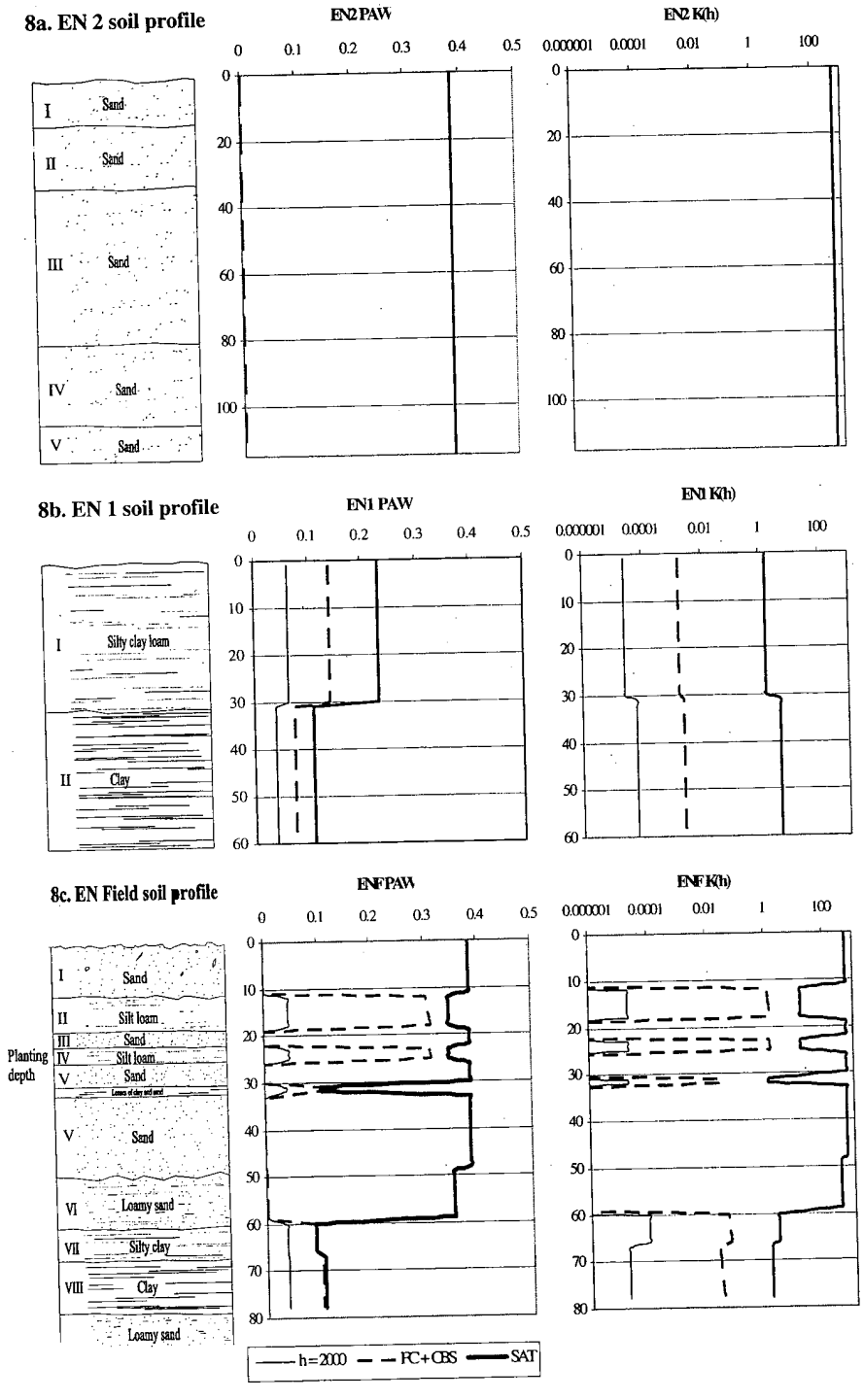

Figure 8. Sample of soil profiles recorded in and near the hand-cultivated EN field.

Stormont and Morris's (1998) equation 8, after the soil has drained to FC. It is assumed that plants cannot extract additional water at –15,000 cm and that $PAW_{15,000}$ is equal to 0 for all strata.

In the EN2 profile of nearly homogeneous sand in Figure 8a there is no capillary barrier storage. At saturation, the value for $K(h)$ is approximately 713 cm/day. PAW_0 is high: within the 55-cm-thick root zone (where roots are dense to common), the soil could hold 24 cm of PAW at saturation. The soil can infiltrate surface water at a rate of 30 cm/hr, much greater than the rates of precipitation or most surface runon. However, after draining to FC, $K(h)$ falls to .01 cm/day. PAW_{fc} is .0005 cm/cm, and the root zone contains only .03 cm of PAW. Little additional water can be extracted from the soil as it dries to a matric potential of –2,000 cm. In summary, in a homogeneous sand with no barrier to drainage, little moisture will be available for extraction by plants at FC, and conductivity will be extremely low. It is likely that the sparse, small plants present around the EN2 profile reflect these soil moisture characteristics.

In the EN1 profile of silty clay loam over clay (Figure 8b), there is no capillary barrier storage. The low saturated conductivity in the clay of the weathered bedrock would form a permeability barrier that could limit drainage loss to .02 to .2 cm/day, excluding flow through structural voids (in this case desiccation cracking). The 30-cm-thick root zone could hold 12.9 cm of PAW at saturation. However, it is likely that infiltration of rain or runon into the profile would be limited, due to the low saturated conductivity of the surface stratum: K_{sat} is .07 cm/hr, well below the average .32 cm/hr intensity of storm events in April to September, and runoff loss will occur commonly. After draining to FC, the root zone would hold approximately 4.2 cm of PAW, and the hydraulic conductivity would decrease to .002 cm/day. The low conductivity will potentially limit loss to bare soil evaporation but will additionally limit the rate at which plants can extract water. At $h = 2{,}000$ the root zone would contain approximately 1.9 cm of PAW. These estimates suggest that this profile can hold up to 12.9 cm of PAW in the 30-cm-deep rooting zone, loses moisture to drainage and bare soil evaporation slowly, and retains 4.2 cm of water at FC. However, the infiltration of water into the profile will be limited, and water will not be easily extracted by plants. It is likely that the sparse, small plants present around the EN1 profile reflect these characteristics.

In contrast, the soil profile recorded in the EN field (Figure 8c) has four stratum boundaries that can form capillary barriers: silt loam over sand at the strata II/III and IV/V boundaries and a lens of clay over sand within Stratum V and the strata VIII/IX boundary. At saturation, the profile would hold 24.5 cm in the 80-cm-thick root zone. When the sandy and loamy sand strata drain to FC, additional moisture would be retained from drainage by capillary barriers. With this condition, the head at each of the boundaries would remain at the breakthrough head of fine sand, 24 cm. The head above the boundaries would decrease by 1 cm per vertical centimeter of soil to the top boundary of the stratum. Without capillary barriers, the 67-cm-thick root zone would hold approximately 3.0 cm of PAW at FC, but the capillary barriers can retain up to 2.3 cm of additional water, for a total of 5.3 cm of PAW. When dried to –2,000 cm of matric potential, the total PAW held in the root zone would be 1.3 cm, assuming that additional water held by barriers would be extracted and that the profile would equilibrate to –2,000 cm.

The EN field profile (Figure 8c) contains strata with conductivity characteristics that will serve to increase moisture input and decrease rates of moisture loss, as well as zones with consistently higher conductivity that allow rapid moisture extraction by plants. The upper stratum of sand can infiltrate precipitation or surface runon at 30 cm/hr, higher than rates of precipitation and most runon events. This is because the stratum is 11 cm thick and has a porosity of .43. Consequently, it can absorb up to 4.7 cm of water before it would be filled, 20 times the magnitude of the average April–September precipitation event of .23 cm. Runoff loss will occur infrequently. Once the wetting front of the infiltrating water reaches the silt loam of Stratum II, the infiltration rate will decrease to a minimum of .45 cm/hr (Jury et al. 1991:83–87). In the period following the input of surface water, the surface stratum of sand will drain rapidly to FC, and hydraulic conductivity will decrease to <.0001 cm/day, limiting loss to bare soil evaporation (Figure 8c). The sandy strata will drain to FC, and conductivity in these strata will be <.0001 cm/day. In the finer-textured strata above the capillary barriers, matric potentials will remain at smaller values,

and values for conductivity will remain as high as 3.9 to 8.3 cm/day in these strata (Figure 8c). If head values in all strata equilibrate at –2,000 cm, conductivity in the sandy strata will decrease to $<10^{-5}$ cm/day but will remain as high as .02 cm/day in the strata of finer textures.

In summary, the EN field profile is an example of a profile in a currently farmed field, consisting of strata of highly contrasting textures and hydraulic characteristics. Estimates of hydraulic conductivity indicate that the surface stratum of sand can infiltrate large quantities of water during input events, but the subsequent decrease in conductivity to the surface will decrease loss of water to bare soil evaporation. Subsurface strata of sand and loamy sand will contain very small quantities of water that is almost nonconductive after the soil has drained to FC. However, in the subsurface strata with finer soil textures, PAW and conductivity remain high. It is likely that crop growth in the EN field is promoted by these soil/water relationships, in contrast to the conditions in and around the EN1 and EN2 profiles, where plants of key taxa are thin and small.

Field Clearing

Hopi farmers state that a high degree of transpiration loss is eliminated by removal of the natural vegetation (e.g., "They [the shrubs and grasses] are the only ones drinking here"), making water available for crop plants. In natural plant communities, individuals of both perennial and annual taxa cover the soil surface to the density that moisture and insolation will allow. Perennials are always present, and many taxa can transpire moisture during any period when temperatures and soil moisture are sufficiently high (Fire Effects Information System n.d.). In contrast, traditional Hopi agriculture eliminates all plants from a field except the crop, which is present from planting (April–June) until harvest (July–October), as well as a small number of useful plants. Field clearing conducted months in advance of planting allows a period of moisture recharge.

Traditionally, clearing was done by hand with the wooden digging stick (*so'ya*) and wooden clearing stick (*wikya*); and it has been done more recently with steel hoes, mattocks, and shovels (e.g., Underhill 1946). Currently, most farmers use tractors when possible, and hand tillage is infrequently practiced. As taught by Second Mesa farmers, traditional clearing uses a hoe or wikya on herbaceous plants and smaller shrubs to sever the upper plant (shoots) from the root system 2–7 cm below the ground surface. Larger shrubs require a mattock, shovel, or axe or might be levered out of the ground. Farmers state that larger roots should be removed, since they can harbor worms that damage or kill young crop plants. Larger detritus is moved to the edge of the field and is sometimes burned. To remove a particularly stubborn woody plant, the farmer removes as many branches as possible and allows detritus from clearing to dry for several days. The farmer then piles detritus over the remaining plant and burns the remaining parts. Farmers often avoid dense stands of Mormon tea and stands of particularly tall, dense shrubs due to the labor required. They prefer to clear adjacent areas of smaller shrubs.

Clearing causes minimal disturbance to the soil profile. With the exception of very large shrubs or trees, only the bases of plants are hoed, and patches of bare soil often remain unhoed. Field clearing thus creates a shallow, discontinuous layer of disturbance with small, infrequent areas with deeper disturbances. Many soils of the Hopi area are subject to erosion, and minimal tillage leaves the surface intact and less subject to erosion (Prevost et al. 1984). Stewart and Nicholson (1940:47) state that the Hopi never favored the plow because it increases the hazard of wind erosion.

Clearing proceeds incrementally into new areas, generally following stands of key plants, sandy soil surfaces, and drainage patterns. Clearing can proceed rapidly among herbaceous plants and shrubs that are up to 1 m tall and thin to moderate density. The timing of this activity indicates that in these conditions, a farmer can clear at an average rate of 40 m^2/hr (with breaks), creating an area sufficient for 5.5 corn clumps in 1 hr.

Weeding

Transpiration loss to weeds can be significant, and the removal of weeds is important for conservation of moisture (e.g., Forde 1931:389; Stewart 1940:335). There is a high degree of variation in the effort required to control different taxa of weeds: some have tough stems, and some can regenerate from roots. Frequent hoeing reduces the seeding and establishment of weeds. It also reduces the size

and density of weeds, so that transpiration loss rates are smaller. Manolescu (1995:29–30) has found that fields that are well tended produced more corn per unit area: an average of 109 kg/ha (97 lb/ac; $N=5$) from fields with "Fair" weed control, 137 kg/ha (119 lb/ac; $N=4$) from fields with "Good" weed control, and an average of 221 kg/ha (197 lb/ac; $N=25$) from fields with "Excellent" weed control.

Hoeing also causes shallow and discontinuous disturbance of the soil surface to a depth of 2 to 7 cm. Many farmers use a "chop-and-drag" technique that pulls the weeds and soil in one stroke. Some use a "slice-and-exit" technique that cuts the root on the first stroke, and then the hoe exits the soil without pulling the weeds and soil. The weeds are then pulled on a second stroke above the top of the soil. The latter technique has the advantage of leaving the soil surface unturned and nearly intact. The preferred strategy is to hoe frequently but to use a limited effort at plant removal. The shoots of plants that remain rooted in a field are hoed frequently, eventually killing most. The timing of this activity indicates that, depending on the density of weeds, a farmer can hoe 400 to 1,200 m^2 in an hour (with breaks).

Soil Profile Maintenance and Enhancement

Both ethnographic and MTWCT data indicate the importance of maintaining a layer of sand at the soil surface to act as a mulch. For example, Bowers's (1929) assertion that the Hopi farmer cultivates by hand with a heavy hoe, keeping a soft mulch on top, is similar to that of Beaglehole: "It is necessary to have the subsoil covered with six to eight inches of top soil in order to retain adequate moisture in the ground" (1937:36). Hopi farmers agree that evenly distributed sandy topsoil is important and should be maintained where possible. Along with techniques used in traditional field clearing, subsequent tillage and maintenance activities protect or enhance the soil profile of a field. In creating shallow, discontinuous disturbance, the Hopi techniques of clearing and weeding both preserve and maintain the soil profile.

Farmers agree that soil must be protected from wind erosion. Some techniques extend beyond protection and manipulate the input and loss of sand at the surface. One farmer referred to a state of "stability" for soil: a balance between eolian transport and deposition, where sand deposition promoted by windrows and remaining crop stubble maintains a thin layer of sand in spite of frequent eolian transport. Brush rows and windrows (consisting of uncultivated natural vegetation) help to retain sand (Bowers 1929:456; Stewart 1940:332; Underhill 1946). As observed by Clark (1928:236), windbreaks are generally built across fields by sticking brush upright in the sand, located about 30 ft apart in parallel rows and at right angles to the prevailing winds. Sage and blackbrush are brittle and break off into clumps with a stem that can easily be pushed into the ground. Snakeweed is sometimes placed atop the surface, with the stem up, and rows are anchored with snakeweed stems pressed into the ground. According to Forde (1931) and Stewart and Nicholson (1940), windrows and crop stubble additionally provide protection for plants from blowing sand, as do small windbreaks of stones or brush constructed at the leeward side of each corn clump (Stewart 1940:335).

Areas with excessively deep sand at the surface are sometimes cleared so that wind erosion can remove some of the sand, in a process similar to that described by Beaglehole (1937:36). For example, Figure 9 looks northeast across the EN2 field and shows an area that was cleared the preceding year, allowing wind transport of sand to the northeast, from the foreground to the uncleared background. As the excess sand is deposited over more clayey soil in the background, these areas will be cleared for farming. Brush rows in the foreground control the depth of soil erosion.

Planting Depth and Technique

Deep planting is extremely important, since roots must get to water quickly. Hopi corn is adapted to rapidly root to a deep level and to rapidly grow a long mesocotyl that will initiate photosynthesis (Collins 1914). Beaglehole (1937:40) and Bradfield (1971:6) state that deep planting places seeds in zones of greater soil moisture. As practiced today by Second Mesa farmers, seeds are placed at a depth that feels moist, usually between 15 and 40 cm below the soil surface, similar to observations by Bowers (1929:456), Forde (1931:390), Beaglehole (1937:40), Stewart (1940:334), and Bradfield (1971:5). Collins states that "there is no fixed depth for planting, the custom being to plant deep enough to place the seed into moist soil" (1914:299).

During planting, soil moisture is observed con-

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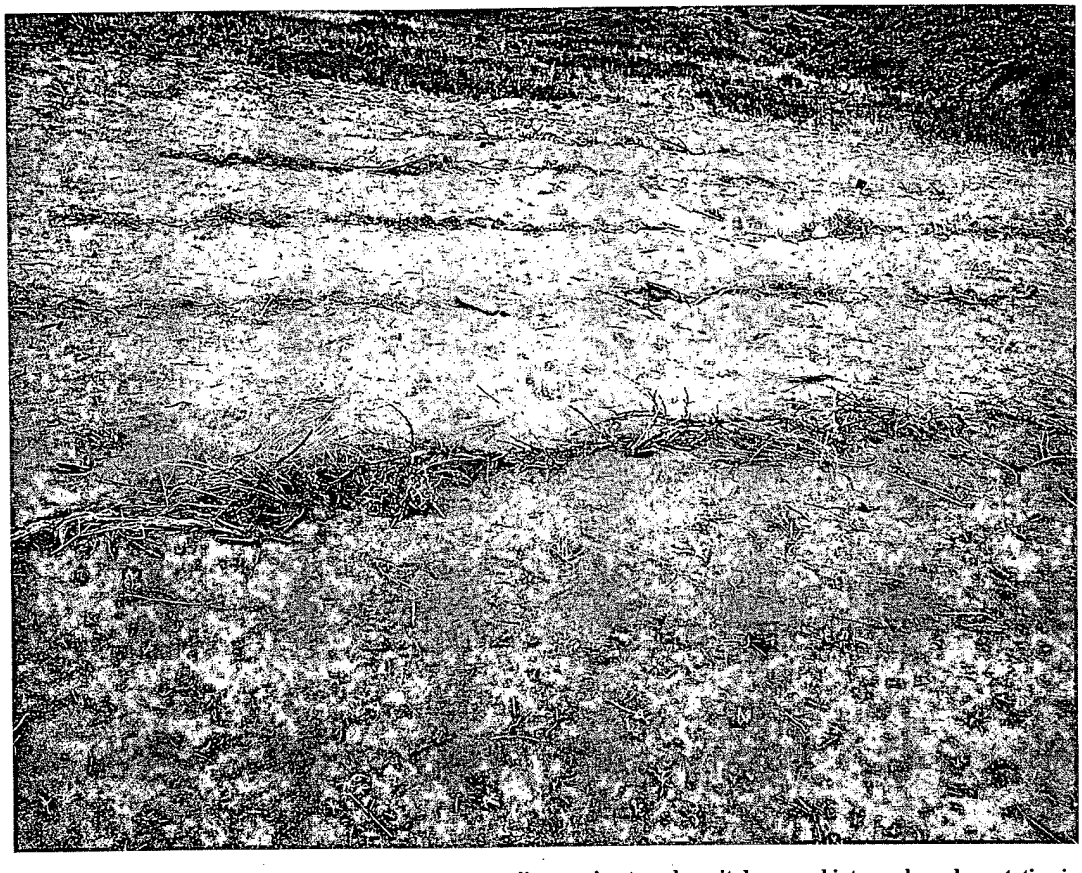

Figure 9. Clearing of vegetation in foreground to allow eolian erosion to redeposit deep sand into uncleared vegetation in background. (MTWCT02/07/17/056)

tinually. At the point where a plant clump is to be sown (Figure 10), the drier upper soil is scraped aside with the foot (consistent with Beaglehole 1937:40; Bradfield 1971:5) to expose moist soil below (Stewart 1940:334). When that is done in a sand-mulched field, it separates the coarser mulch (which drains and dries rapidly) from the finer soil below (which does not drain and dry as rapidly). In so doing, a shallow trench is formed, usually 8 to 12 cm deep by 20 cm wide and 30 cm long. Then, using the wooden so'ya (digging stick) or an iron tool with a chisel-shaped tip (Bowers 1929:456), a deeper, smaller hole is dug into the moist soil (Beaglehole 1937:40). Alternatively, some farmers push the so'ya into the soil and form a conical hole. The small quantity of soil excavated from the deeper hole is left separate from the dry upper soil (Figure 10). This allows the soil from the two layers to be handled separately, decreasing mixing of layers and consequent loss of effectiveness in controlling the movement of soil moisture. Seed is placed into the position where soil moisture feels the highest. Note the association of planting depth with the silt loam Stratum IV in Figure 8c. This is consistent with Clark's assertion that farmers "dug to a stratum of clay—no matter if it be 8, 12, or 15 inches" (1928:235–236).

The presence of silt and loams in the upper part of the profile can be an important factor in determining planting depth, due to the high AWC and the conductivity of water in strata of these textures. In a subsurface stratum of silt or loam, larger quantities of water are stored, hydraulic head is much lower, and moisture is more mobile and more easily absorbed by roots, than near the surface. This promotes more rapid seedling establishment and rooting into moist soil than planting at shallower depths or planting in sandy or clayey soil. Most important, Manolescu (1995:27) has found that productivity in cornfields increases with planting

Figure 10. Planting technique: Mulch scraped aside to expose top of moister soil layer. Seed is placed in smaller hole dug into moist layer. (MTWCT02/05/16/015)

depth up to 38 cm (15 in): an average of 67 kg/ha (107 lb/ac) for fields planted at depths less than 20 cm (8 in) and an average of 183 kg/ha (293 lb/ac) for fields planted at depths greater than 20 cm. Deeper rooting also gives better stability to plants, resulting in fewer plants being knocked over by high winds or overland flow (Beaglehole 1937:40; Forde 1931:390; Stewart 1940:334).

After seed placement, the moist soil is pushed back into the deeper hole (Bradfield 1971:5). The mulch is then pushed back over the trench and smoothed. Some farmers leave a shallow depression 5 to 10 cm deep and 30 to 80 cm across. This can give young plants some shelter from the wind, as well as retaining water from runoff (Forde 1931:391; Stewart 1940:335). The timing of this activity indicates that in soft to slightly hard soil, one person can plant 20 to 30 clumps an hour (with breaks).

Number of Plants in a Clump

As noted by Forde (1931:390), Beaglehole (1937:40), Stewart (1940:334), and Bradfield (1971:5), Hopis plant eight to 20 seeds in each clump. The establishment of such a large number of plants requires the consumption of a higher quantity of water, but there are several advantages. Seeds and young plants are often lost to crows, rabbits, and rodents, as well as cutworms (Beaglehole 1937:40; Forde 1931:390; Stewart 1940:334). Planting a higher number of seeds increases the chance that a sufficient number in each clump will survive. It additionally increases the number of representatives from the existing genetic pool in each clump and therefore increases the probability of planting a large number of individual seeds adapted for the conditions. Planting in clumps provides protection to plants within the clumps, as outer plants are subject to higher PET, as well as damage from wind (Beaglehole 1937:40; Forde 1931:390; Stewart 1940:334; Underhill 1946:30). The effectiveness of planting larger numbers of seeds is emphasized by Manolescu's (1995: tab. 6) data on corn production: an average of 90 kg/ha (145 lb/ac) from five to nine seeds per hill, 147 kg/ha (235 lb/ac) from 10 to 14 seeds, and 161 kg/ha (259 lb/ac) from 15 to 20 seeds (1995:27).

Subsequent thinning of clumps is important, because a larger number of plants will compete more for water as they grow, resulting in smaller

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Table 3. Relationship between Average Yields and Spacing (Adapted From Manolescu 1995: Table 7).

Spacing (m); Manolescu 1995: Table 7	Average yield No. of fields; Manolescu 1995: Table 7	in kg/ha; Manolescu 1995: Table 7	Average Clumps per ha	per-clump production (kg)	Per-clump soil surface area (m^2)
1.5	1	25	4225	.01	2.3
1.8	2	162	2,916	.06	3.2
2.1	7	177	2,209	.08	4.4
2.4	9	193	1,681	.11	5.8
2.7	8	255	1,296	.20	7.3
3.0	5	223	1,024	.22	9.3
3.3	2	72	841	.09	11.2

individual plants and ears. Clumps are thinned from eight to 20 individual plants to five or six of the best plants. This strategy selects in favor of plants that establish and grow quickly.

Clump Spacing

Hopis plant in clumps at widely spaced intervals. For corn, Bowers (1929:456) gives a spacing of 8–12 ft; Forde (1931:390), a spacing of two to three paces; and Stewart (1940:334), Beaglehole (1937:40), and Bradfield (1971:5), three to five "paces." The average row spacing in the 34 fields sampled in 1994 by Manolescu (1995) was 2.7 m (SD = .5), and average plant spacing was 2.8 m (SD = 1.0). The locations of clumps are staggered year to year (Beaglehole 1937:37; Bowers 1929:456; Stewart 1940:334; Stewart and Nicholson 1940:47), with each new clump planted in the middle of the square formed by the prior years stubble. Forde (1931:391), Beaglehole (1937:40), and Underhill (1946:29) state that staggering clumps provides "rest," a fallow period for the soil between clumps.

Spacing influences the surface area over which the soil surrounding a clump can absorb surface water, as well as the volume of soil that can store that water with limited or no competition from other plants. Hopi farmers are aware of the close relationship between plant spacing and production. Observing poor survivorship and production in one field with too-closely spaced clumps, one Hopi farmer remarked, "You shouldn't ask for too much." It is likely that the guidelines for spacing resulted from many years of selection for the spacing that gives the highest yield. Manolescu's 1994 corn production data (Table 3) indicate that per-clump production increased with increasing spacing up to 3.0 m. This suggests that competition for water and other nutrients decreased with increased spacing. However, other factors such as weeding and depth of planting might have additionally influenced results, especially in the sample of two fields with spacing of 3.3 m that show a decrease. Per-hectare production shows a similar increase up to a spacing of 2.7 m, beyond which it declines. This is consistent with limits to increase in production with increasing spacing (Arnon 1975), beyond which increases in per-clump production are of smaller magnitude than the increase in "wasted space" between clumps. The fact that the spacing averages recorded in 1994 by Manolescu (1995) are close to the spacing that gave the highest per-hectare yield is consistent with selection for spacing that gives a high yield.

The total surface area created for each clump by spacing additionally varies by crop. Beans are planted in clumps that are only one-half to one pace apart, and rows of clumps are spaced one pace apart (Forde 1931:390), yielding .5 to 1 m^2 for each. Clumps of melon plants are spaced five paces apart (Forde 1931:391), yielding 25 m^2 for each.

Relating Precipitation and Crop Production

The basic structure for relating precipitation to maximum potential crop production is direct, given values for water use efficiency, the harvest index, and the balance of soil moisture available in the discrete soil volume. Manolescu's (1995) production data provide one example, reporting a 1994 precipitation total of 11.9 cm for Keams Canyon. In this example, it is assumed that this precipitation total is representative for all fields in the sample recorded and that only direct precipitation was received. The assumptions ignore the potential inputs of supplemental water and other factors that affect final production. In fields with a mean spac-

ing of 2.7 m, each clump had a soil surface area of 7.3 m and received .87 m^3 of water from direct precipitation. In these fields, average per-clump production was .20 kg of grain, suggesting that dry matter production was .44 kg, and .17 m^3 of water was consumed by each clump. This suggests that 20 percent of the water received by the DSV of each clump was consumed by the plants, while 80 percent was lost to bare soil evaporation, drainage, and weed transpiration or continued to be stored in the soil.

Because the basic structure of production estimates is direct, WUE, HI, and the estimated percentage of water consumed by plants can be used to estimate maximum crop production. For example, if the fields in the above example received the average annual precipitation of 28 cm, the estimated per-clump grain production would be .47 kg. However, none of the variables used in that estimation can be assumed to be constant. The actual percentage of the precipitation and supplementary water that would be available to plants will vary with the specific soil profile and the particular sequence of water inputs and losses for each year. The WUE and HI are not constant (Ritchie et al. 1992) and vary with the particular sequence of soil moisture levels and the soil nutrients available. In order to determine the degree that prehistoric drought and soil degradation affected agricultural production, it will be necessary to improve our ability to determine the nature of paleoclimatic events, responses of soils to sequences of water inputs, and responses of plants to sequences of soil moisture levels. The concept of the DSV, the use of soil hydrological principles, and crop growth modeling software (such as DSSAT 3.5) can help to further some of these necessary developments.

Discussion and Conclusions

In this article, the soil hydrologic processes affected by Hopi agricultural practices are identified, conceptually modeled, and quantified. This preliminary, general framework identifies variables necessary for further evaluation of interactions among soil hydrologic processes, technology, and climate inputs in other spatial and temporal contexts.

Information collected during this project suggests that Hopi field selection and cultivation techniques are greatly influenced by soil profile characteristics and consequent processes of soil moisture storage and movement, as well as by prospects for accumulating supplementary water. Hopi farmers' evaluations of the farming potential of various settings suggest that soil profile attributes are more important considerations than are the prospects of gaining supplementary water. During interviews, Hopi farmers did not consider locations in drainages and alluvial fans that lack appropriate vegetation conditions to be suitable for farming. Instead, they preferred locations with appropriate vegetation conditions, even if they were on hill slopes, summits, interfluves, or other locations without sources of supplementary water. This suggests that the soil attributes and moisture conditions implied by the presence of a dense, vigorous stand of key taxa are considered by the farmers interviewed to be a necessary condition for farming.

That assertion does not challenge the validity of prior work (especially Bryan 1929; Hack 1942) that asserts the importance of locating fields where supplementary water is available. The modeling and applications of vadose-zone hydrology have primarily developed since 1980, long after those seminal publications, and those authors emphasize processes understood at that time. Further, this should not be construed as an "either–or" choice of which processes operate in any location. Rather, it identifies a second set of processes that operate in concert with the processes identified by Bryan (1929), Hack (1942), and other investigators. The fact that the storage of direct precipitation and use of supplementary water are important complementary processes is underscored by Manolescu's (1995) data, which show that fields with sources of supplementary water produced approximately two times the quantities of grain as fields without them.

In Hopi farming, the selection of a location is the beginning of an experiment. The success of the experiment and continued use of the location are dependent on the moisture conditions present in the field, interactions of soil hydrology with farming techniques, and consequent crop production. The distribution of farmed lands is thus a result of this selection process, as well as landownership. Farming techniques are also subject to experimentation, and the existing techniques should be viewed as a result of centuries or millennia of selection (consistent with Brandt 1995).

Traditional Hopi agricultural technology effectively uses both direct precipitation and supplementary water. Plant clump spacing and planting depth improve crop consumption of moisture, by providing a sufficiently large volume of soil from which to extract water and by placing seed into moister soil that also gives less resistance to water extraction by plants. The high number of seeds planted in each clump introduces a large number of individual plants into competition for water, and the subsequent thinning of smaller individuals retains the individuals that can best thrive in the existing moisture conditions. Frequent weed removal eliminates competitors for moisture. Hand-cultivation techniques, including tillage, planting, hoeing, and windbreak construction, preserve or enhance the soil profile and decrease water loss to bare soil evaporation. In summary, Hopi agriculture functions by selecting soils that maintain higher soil moisture and limiting the losses to drainage, bare soil evaporation, and transpiration by competitors.

The data presented by Manolescu (1995: tab. 7) and further explored in this article (Table 1) suggest that low plant density is a key attribute of Hopi farming that increases production in each clump. This attribute additionally provides an advantage in modeling soil moisture balance and crop production. Plant clump spacing defines the soil surface area between plants and permits estimation of the maximum quantity of water that can be absorbed from precipitation and runon into the soil in the intervening surface area. In conjunction with soil attributes in and near the root zone, spacing defines the discrete soil volume available to act as a moisture reservoir for each clump. Using a "clump-based" model of agriculture, in conjunction with crop water requirements (e.g., Gardner et al. 1985:95), it is then possible to directly link the soil moisture levels resulting from Hopi farming practices to the potential yield of dry matter and grain production. This deterministic method can reduce the problems of using empirical data derived from fields of undocumented plant densities and, consequently, indeterminate moisture budgets to estimate production. In determining the relevant variables and physical models, these results will promote the development of physically based, deterministic methods to estimate the range of climate conditions in which soils with different profile attributes can operate.

The omission of soil fertility in this research is not an oversight and does not imply that it is not important. Agronomic studies do indicate more efficient use of water with higher levels of nutrients (e.g., Arnon 1975; Hanaway 1962). Rather, the emphasis on moisture balance is based on assertions that water is more limiting than fertility in environments where direct precipitation is less than 50 cm (e.g., Leith and Whittaker 1975; Muenchrath and Salvador 1995).

In summary, Hopi field location criteria identify locations with higher soil moisture as indicated by the condition of the natural plant community. The techniques employed during the removal of the natural vegetation and cultivation of a crop have limited impact on the environment, and soil profile attributes that serve to promote the accumulation and retention of water are preserved or enhanced. Traditional Hopi agriculture depends on the physical interplay among specific soil/bedrock arrangements and precipitation. It also depends on the skill and application of labor that utilizes and preserves the arrangements provided by the natural environment. Hopi agriculture is cultivation in its most parsimonious form: finding a location that is highly suited to the cultivars and, with limited modifications to the physical environment, replacing the natural vegetation with a crop. Ideally, Hopi farming could fit seamlessly into the habitat, without altering its functioning.

Implications for Southwestern Archaeology

Clarification of climate/soil/technology interactions using generalized soil hydrology principles will ultimately provide archaeologists with means to evaluate the distribution of locations that could produce crops with hypothesized farming technologies. With further development, the resulting concepts and estimation techniques will promote accurate evaluations of crop production in diverse cultural, geomorphic, and climatic conditions. Similarities among technologies observed in various portions of the Southwest suggest that a general strategy might have existed in some areas. At the same time, there is a high degree of variation in the environmental and cultural conditions across the Southwest and through time. A generalized analytic technique can form the basis for comparisons

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among these settings.

Information included with soil classifications provides clues to the agricultural potentials of soils, and soil maps provide clues to the distributions of potentially productive soils. However, there is a need for a generalized method to evaluate potential soil moisture conditions regardless of soil genesis, including those in soil profiles that result from natural variation in soils or in humanly modified portions of the landscape. Preliminary evaluations can be provided by the estimation technique applied to the sample of three soil profiles in the EN field. Soil moisture contents and hydraulic conductivities are easily estimated and graphed using a spreadsheet. The resulting profiles of soil moisture contents and conductivities have the assumed conditions of equilibration and represent preliminary estimates. The actual distribution and conductivity of water in soil profiles are subject to the sequence of moisture inputs and losses and are best estimated using digital simulations and calibration with the results of soil moisture monitoring.

There is additionally a need to evaluate the hydrologic effects of hypothesized farming technologies. Preliminary assessments of the effects that soil maintenance or modification have on soil moisture content and mobility can be estimated using the technique applied to the evaluation of profiles. Preliminary estimations of the effects of plant spacing and climate inputs are possible with the moisture balance approach of the DSV.

There are three potential limitations on applying the proposed DSV model to analyses of prehistoric agricultural production. First, we cannot know that current Hopi or any other Southwestern traditional technologies were indeed used by any prehistoric people. We can only surmise the nature of prehistoric technology, based on ethnographic analogy (e.g., Homburg and Sandor 1998) and the nature of the infrequent remains of cultivars, agricultural features, and tools. However, existing traditional technologies are probably the result of a long period of transmission of ideas and selection, and these are probably reflected in modern traditional farming practices (Brandt 1995). In future research, core technological attributes common among the descendants of the early Pueblo people might be identified through contrasts among the traditional technologies of the various Pueblo peoples.

The second limitation is that it is not yet known whether traditional Hopi farming technology can be transferred to other environments. It is possible that field site selection techniques, based on soil/plant relationships, will not work in dissimilar environments where the key taxa are absent or rare, although analogous soil/plant relationships may exist. Additionally, Hopi cultivation techniques might not work in other environments with dissimilar soil profiles, topography, or rainfall/runoff relationships, although analogous environmental attributes might exist in other Southwestern contexts. To address these problems, an experimental project is being proposed to determine if Hopi technology can operate in southwestern Colorado. Until resulting data are available, deterministic hydrologic models can help to assess the prospects.

Third, it is necessary to assess the degree of change in soils and plant/soil relationships that occurs during and after the use of an area by farmers. Both soil erosion and deposition can affect the depths and layering of soils. Climate-induced changes in soil/plant relationships can obscure the clues that prehistoric farmers might have used to locate arable soils. However, changes in soil have a relatively conservative, predictable effect on the hydrologic functioning of a landscape: changes in landscape attributes can be evaluated using geomorphologic techniques, and the hydrologic functioning of soil profiles can be modeled using physically based deterministic methods.

In assessing the prospects for modeling prehistoric agricultural production, it is necessary to consider that the results from a time-series simulation of soil moisture and crop production are only as good as the models employed. The advantage of using a physically based, deterministic model is that relevant agricultural variables can be controlled during simulations; but they cannot be controlled while using calibrated, empirical models. With deterministic models, variables can be adjusted for both real and hypothetical conditions. This will make it possible to evaluate the potential productivity of a landscape over a wide range of soil profile attributes, crop types, plant spacing, and precipitation and temperature series. Such models can be improved as new information becomes available, as well as being adjusted for dissimilar climatic and geomorphic environments.

In spite of these caveats, archaeologists can make preliminary, conceptual assessments of the

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extent of arable lands in a study area, using commonly published data and concepts gleaned from Hopi farmers. The distribution of key taxa on a geomorphic landscape can be determined in environments where they are present in sufficient numbers. The identification of analogous plant/soil relationships in an environment dissimilar to Hopi would require further evaluation of phytogeomorphology and pedology. The geologic, geomorphic, and pedologic attributes of a landscape also yield important clues to prospects for farming. The nature of the bedrock (e.g., whether it is permeable sandstone or impermeable shale) influences the movement of water below and near the soil surface and much of the hydrologic cycle of an area (e.g., Dingman 1994; Freeze and Cherry 1979). The geomorphic processes that affect deposition and the parent materials available for deposition determine the distribution of soils with good moisture retention. Evaluations of AWC and soil depth, as provided in NRCS reports, provide excellent clues to the agricultural potential of a soil (e.g., Herhahn and Hill 1998; Van West 1994). However, due to the fact that soils are more variable than indicated by NRCS, that information should be augmented with profile data collected from the study area. Most important, analysis of the hydrologic functioning of an agricultural plot or any type of water-control device is most effective when considered in the context of the full hydrologic cycle of the entire catchment it occupies.

It is not necessary to evaluate a model mathematically to develop a preliminary, conceptual model of an agroecological system (Kolm et al. 1996). Mathematical modeling can be used later to verify the model and determine the range of climate conditions that allow farming in the various soils represented. Analysis of the effectiveness of soil profile attributes in retaining moisture can provide preliminary evidence in an evaluation of landscape use. The results of subsequent pollen studies can verify farming in a sample of sites, adding further evidence regarding the agricultural use of soil types present in a study area. Future publications will provide further details on methods for the conceptual and mathematical assessment of arable land distribution and climatic limits for crop production. It cannot be confirmed that elements of traditional Hopi agricultural technology were indeed used by prehistoric agriculturists of the North American Southwest, but study of the relationships between that technology and soil hydrology has yielded a set of principles that are complementary to the principles of water harvesting and can help to focus our research on prehistoric crop production.

Appendix A: The Van Genuchten (1980) Equations

Moisture characteristic curve:

$$(h) = \theta_r + (\theta_s - \theta_r)[1 + (\alpha h)^n]^{-m}$$

Unsaturated hydraulic conductivity:

$$K(h) = K_s[1 - (\alpha h)^{mn} (1 + [\alpha h]^n)^{-m}]^2 / [1 + (\alpha h)^n]^{ml}$$

Both equations use parameters measured for each soil texture. These include the following:

h = matric potential, suction head

θ_r = volumetric soil moisture retained at very high values of h (>>15,000 cm)

θ_s = volumetric soil moisture at saturation ($\theta_s = \varphi$, soil porosity)

α = fitted parameter

n = fitted parameter

$m = 1 - 1/n$

l = pore conductivity parameter, usually assumed to be 1/2

The hydraulic parameter values for the θ_r, θ_s, α, n, and K_s of soil textures discussed in the text are given in Table 4. Values for other textures are given by Carsel and Parrish (1988).

Table 4. Parameters for Soil Textures Discussed in Text.

Soil Texture	θ_r	θ_s	α(cm^{-1})	n	K_s(cm/hr)
Sand	.045	.43	.145	2.68	29.7
Loamy sand	.057	.41	.124	2.28	14.6
Silt loam	.067	.45	.020	1.41	.45
Silt	.034	.46	.016	1.37	.25
Silty clay loam	.089	.43	.010	1.23	.07
Silty clay	.070	.36	.005	1.09	.02
Clay (<60% clay)	.068	.38	.008	1.09	.2

Source: Carsel and Parrish 1988.

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