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A MAIZE EXPERIMENT IN A TRADITIONAL ZUNI AGROECOSYSTEM

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*Maize has sustained the Zuni and other people in the arid American Southwest for many generations. In the traditional Zuni dryland agricultural system, fields are carefully placed on valley-edge landforms to tap into watershed hydrologic and ecosystem processes. In these geomorphic positions, field soils are managed to receive supplemental water and nutrients for crops by retaining storm runoff transported from adjoining uplands. Crop experiments were conducted to examine the effects of runoff on maize (*Zea mays*) productivity. Productivity of a Zuni maize cultivar and modern hybrid maize was evaluated with five treatment combinations of water and nutrient input sources in two traditional agricultural areas that have been cultivated for at least 1000 years. During the first year of the two-year experiment (1997–1998), one field received inputs from four runoff events, while the other field, with a larger watershed, received no runoff. In year two, the one remaining field (the other field was disrupted) had inputs from one runoff event. Growing season precipitation was above average for both years of the experiment. All treatments, including those receiving only precipitation, produced grain yields ranging from 852 to 3467 kg ha^{-1} for Zuni maize. Grain and biomass productivity tended to be greater in the irrigation-plus-fertilizer control treatment. Productivity differences among treatments are attributed primarily to differences in water inputs rather than nutrient supply. Although the more densely populated hybrid maize out-yielded Zuni maize on a land area basis, Zuni maize produced greater yields per plant and more biomass than did the hybrid maize.*

Keywords: *maize, American Indian agriculture, water harvesting, runoff agriculture, American Southwest*

Introduction

Rising demand for water, environmental degradation, and the threat of global climate change challenge the long-term sustainability of agriculture in arid and drought-prone regions of the world (Nabhan 2013; United Nations Environment Management Group 2011). About one-third of the global land area has an arid to semiarid climate. Worldwide, water is a critical limiting resource for crop production and a high proportion (about 70%) of global water use is for agriculture (Lal 2015).

Over 80% of the world's cultivated land is rainfed, producing more than 60% of the world's food production (Wani et al. 2009). Productivity of rainfed

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agriculture can benefit from supplemental use of runoff in water harvesting systems (Jägermeyr et al. 2016; Rockström et al. 2010). Water harvesting methods in runoff agriculture have been successfully used in traditional and modern agricultural systems in several world regions (Nabhan 2013; Wani et al. 2009).

Rainfed and runoff agriculture have been practiced for centuries by the Zuni and other peoples in the arid southwestern United States and northern Mexico (Bohrer 1960; Cushing 1920; Doolittle, 2000; Hack 1942; Ferguson and Hart 1985; Kintigh 1985; Nabhan 2013). The Zuni are one of 19 Pueblo tribes of New Mexico and Arizona. The Zuni area comprises one of the most continuously inhabited and cultivated lands of the Southwest (Damp 2007) and contains some of the oldest known dryland (non-irrigated) fields in the United States. Archaeological and historical evidence documents Zuni dryland and irrigated fields that are at least 1000–3000 years old (Damp 2007; Homburg et al. 2005) and maize has been grown in the region for about 4000 years (Adams 2015:18). Traditional agriculture at Zuni and other Southwestern Indian communities provides models of diverse and enduring systems. Expanded understanding of their adapted cultivars and the agroecological structure and function of these systems can contribute to the development of sustainable agricultural strategies to successfully meet the challenges of increased water demands in arid regions (Adams 2015; Sandor and Homburg 2015).

Runoff agriculture is remarkable in its ability to supply water and nutrients to crops and to replenish soils without conventional irrigation or fertilization. This is done by connecting fields to hydrologic and ecosystem processes in watersheds. Traditional Zuni fields are carefully placed and managed on valley margin landforms, such as alluvial fans, to receive runoff and associated sediment and organic debris transported from adjoining uplands (Homburg et al. 2005; Muenchrath et al. 2002; Norton et al. 2003, 2007a, 2007b; Sandor et al. 2007). A substantial body of knowledge underlies this agricultural system (Muenchrath et al. 2002; Pawluk 1995; Sandor et al. 2006).

In partnership with the Zuni Tribe, studies to better understand ecological, hydrologic, soil, and agronomic components of traditional Zuni agroecosystems have been conducted (Homburg et al. 2005; Muenchrath et al. 2002; Norton et al. 2002, 2003, 2007a, 2007b; Sandor et al. 2007). Results of the crop experiment part of the project are presented in this paper. The objective of the experiment was to evaluate maize productivity of traditional Zuni agriculture in response to water and nutrient inputs. Findings from this maize experiment contribute to knowledge about traditional dryland agriculture in the American Southwest and elsewhere because it was a scientifically controlled experiment with replicated plots at two sites for two years. The study quantified inputs of water and nutrients, measured several maize production variables, and was conducted in situ within traditional fields.

Environmental Setting

The Zuni Indian Reservation is located in the arid to semiarid mesa country of western New Mexico in the southeastern part of the Colorado Plateau

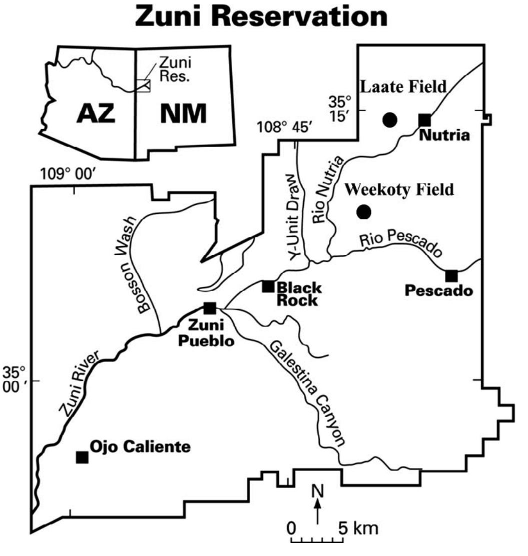

Figure 1. Map of Zuni. Maize experiment fields (Laate Field and Weekoty Field, shown by black circles), located near the traditional farming villages of Nutria and Pescado.

(Figure 1). Elevation ranges from 1838 m near the Arizona border to 2347 m on eastern mesas near the Continental Divide. Narrow canyons to broad alluvial valleys separate mesas. For additional information about the environmental setting, see Homburg et al. (2005), Norton et al. (2003, 2007a), Sandor et al. (2007), and Zschetzsche (2005).

Precipitation and temperature are the primary plant production constraints. Annual precipitation at Black Rock/Zuni, in the central part of the reservation at 1967 m elevation, averages 302 mm (range 112–468 mm, CV 26%; Benson 2010; Western Regional Climate Center [WRCC] 2016). High temporal and spatial variation in precipitation is characteristic of the region now and in the past (Balling and Wells 1990; Benson 2010; Norton 2000; Rhode 1995). Approximately half of the annual precipitation occurs during the growing season, mostly during the summer monsoon season—usually July through September. Summer rains ordinarily occur as brief, highly localized, intense convective thunderstorms, though runoff-causing storm events can be more extensive. Traditional runoff agriculture depends on these monsoonal rains, both during the growing season and for long-term soil formation and replenishment through runoff sediment additions (Norton et al. 2007a; Sandor et al. 2007). The remainder of annual precipitation is received as lower intensity rain or snow from November through March and snowmelt is an important source of moisture early in the growing season. Spring and early summer are dry and windy. The annual freeze-free period at Black Rock averages about 138 days (Benson 2010; WRCC 2016) and is generally shorter at higher elevations. Spring and early summer night temperatures are often well below the 8 °C to 10 °C minimum required for maize growth (Shaw 1988).

Methods

Methods used in the maize experiment are summarized here. Additional details about the experiment are presented in Supplement A.

Maize Experiment Sites

The maize experiment was conducted in two of three intensively studied areas of the larger research project near traditional farming villages in the eastern Zuni Indian Reservation (Sandor et al. 2007; Figure 1). The two experimental fields (Laate and Weekoty) are within traditional farming areas located on alluvial fans at the mouths of ephemeral drainages (Norton et al. 2007a, 2007b; Sandor et al. 2007; Figure 2A, B; Table 1). The fields, 11 km apart and at similar elevations (2072–2088 m), have a long record of historic and prehistoric farming (Table 1). The watershed size at the Weekoty Field (125 ha) is larger than that at the Laate Field (7 ha). The experiment was done at both fields in 1997 and repeated in the Weekoty field in 1998. The Laate field was eliminated from the study in 1998 because sheep were corralled in it during the intervening winter and the manure addition disrupted experiment treatments.

Field sites were established in 1996 by fencing a 0.2 ha area in each field and collecting soil samples to provide baseline information. Prior to planting in 1997, each field was moldboard plowed, harrowed, and divided into 25 plots (see section on experimental design), each measuring 7.5 by 7.5 m. A 3 m border area was left between the plot area and field perimeter fence. Care was taken in 1998 to avoid mixing soil from one plot to the next.

To control treatment applications, each plot was subdivided into 25 areas (subplots or maize "hills" of 2.25 m^2 each). These areas were separated by earthen berms, about 15–20 cm high and wide, creating a grid of bunds or "waffle" appearance analogous to traditional Zuni waffle gardens (Figure 2C, D, E). The bordered plots allowed even application of water and nutrients in specific treatments.

Frequent hand-hoeing controlled weeds; no herbicides were applied. A three-meter-high fence was built around each field to exclude large animals. The crop was protected from bird predation by a grid of transparent fishing line attached to the fence tops. Although insects were observed in the field and affected some plots, no control measures were taken and damage was limited.

Weather and Environmental Information

Weather conditions were monitored each growing season (Figures 3 and 4; Table 2). Precipitation and daily minimum and maximum air temperature data were collected at the Weekoty Field using a remote weather-precipitation station with a CRX-20 datalogger (Campbell Scientific Equipment, Logan, UT). Two funnel collection devices were installed adjacent to each field to measure and sample precipitation. Growing degree days (GDD) were calculated using 10 °C as the base temperature and minimum limit and setting 30 °C as the maximum limit (Cross and Zuber 1972).

Figure 2. Photos of maize experiment fields. A – Laate Field and runoff catchment; B – Weekoty Field; C – Runoff delivery to maize plots; D – Hybrid maize, note lack of tillers; E – Zuni maize, note tillers and greater biomass than in Hybrid maize.

Data relevant to crop production on soils, geomorphology, surface hydrology, and vegetation were collected at the experimental fields and their watersheds and at nearby traditional fields (Homburg et al. 2005; Norton et al. 2003, 2007a, 2007b; Sandor et al. 2007).

Maize Cultivars and Planting

For Zuni and other traditional communities in the region, maize provided sustenance for millennia and continues to be culturally significant today (Adams 2015; Bohrer 1960; Cushing 1920; Ford 1994; Muenchrath and Salvador 1995). Locally adapted, open-pollinated maize (*Zea mays*) cultivars are the staple crop produced by Zuni farmers in runoff fields (Muenchrath et al. 2002). Two types of maize were tested in the cropping experiment (Table 3). Zuni blue maize (with

Table 1. Environmental and cultural information about the maize experiment sites.

Parameter	Weekoty field	Laate field
Elevation	2088 m	2072 m
Watershed size	125 ha	7 ha
Aspect	East	Southwest
Slope	2–3%	4%
Landform	Alluvial fan	Small alluvial fan
Soil parent material	Loamy to sandy alluvium derived from Cretaceous sandstone and mudstone.	Loamy alluvium derived mainly from Cretaceous mudstone.
Soil classification	Fine-loamy, mixed, mesic Aridic Argiustoll.	Fine-loamy, mixed (calcareous), mesic Aridic Ustifluvent with buried argillic horizon.
Cultivation history[a]	Periodically farmed since ca. AD 1000, most recently cropped in late 1980s.	Historic cultivation within experiment field boundaries, area farmed since ca. AD 1000, and near traditional farming village.

[a] Based on archaeological evidence, historic documentation, and information provided by the farmers (Homburg et al. 2005; Muenchrath et al. 2002; Norton et al. 2003; Sandor et al. 2007).

floury-flinty endosperm) seed for the experiment was grown by a local farmer near the traditional Zuni farming village of Ojo Caliente (for more information about this maize, see Adams et al. [2006] and Werth [2007]). Two modern commercial F1 varieties (Hybrid) recommended by New Mexico State University Cooperative Extension Service as suitably adapted for regional conditions were mixed equally and included in the study as a frame of reference to link results to other maize studies, which commonly focus on dent hybrids.

Before planting, Hybrid and Zuni seed were soaked in water for approximately 15 hours. Zuni farmers sometimes soak seed overnight to two days before planting to promote germination (Muenchrath et al. 2002). Maize was planted in the traditional Zuni manner—in clusters (hills, considered subplots) of multiple plants spaced 1.5 m apart. Six kernels were sown in a single hole at the center of each subplot by hand, for a total of 25 hills per plot. Each cultivar was

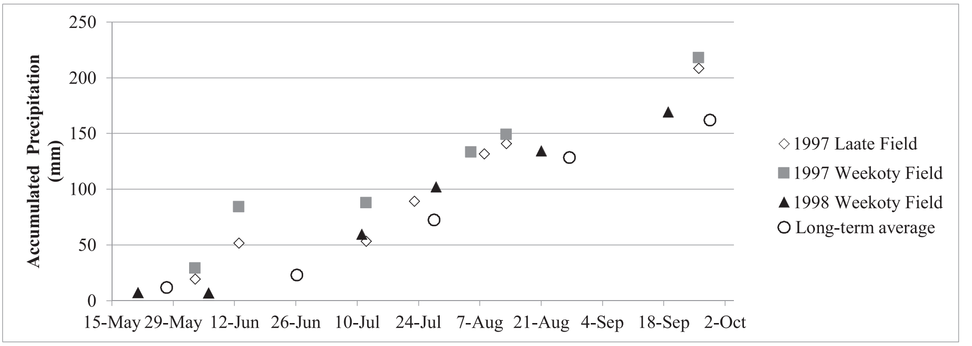

Figure 3. Accumulated precipitation during the 1997 and 1998 growing seasons at the Weekoty and Laate Fields, and long-term (1949–2001) averages at official weather station at Zuni-Blackrock (data from WRCC 2016).

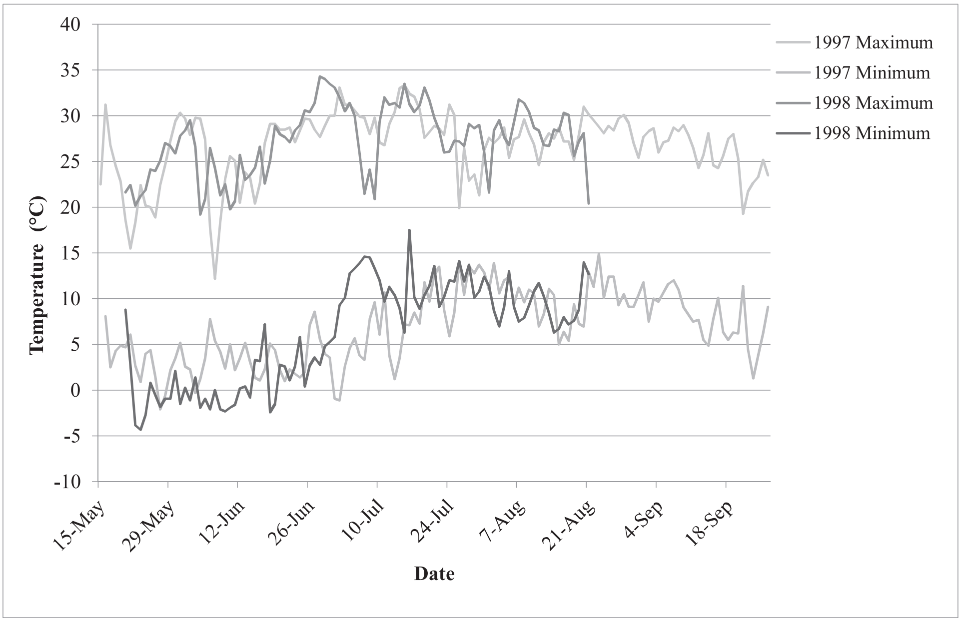

Figure 4. Daily minimum and maximum air temperatures at the Weekoty Field weather station.

Table 2. Growing season (May through Sept.) rain (precipitation) amount and monthly distribution by field-year, and at official Zuni weather station at nearby Black Rock, New Mexico each year and long-term average (1949–2001). Field amounts are the average of the two funnel collection devices at each field for 16 May through 26 Sept. 1997, and 20 May through 19 Sept. 1998.

	Growing season total rain	Rain amount and events[a]				
		May	June	July	Aug	Sept
Field-year	(mm)	mm and (number of events)				
Laate 1997	208.9	19.6 (–)	32.2 (–)	37.6 (–)	51.7 (–)	67.8 (–)
Weekoty 1997	218.4	29.5 (7)	54.9 (5)	3.9 (11)	61.2 (17)	68.9 (12)
Black Rock 1997	203.5	21.6	40.9	26.4	93.0	21.6
Weekoty 1998	169.6	0.8 (1)	0.1 (1)	101.4 (17)	32.3 (10)	35.0 (–)
Black Rock 1998	172.7	0	0	90.7	46.5	35.5
Long-term average	159.7	11.6	10.5	49.5	57.5	30.6

[a] Rain event data were collected only at the Weekoty field. Although automated weather station malfunction resulted in missing data after 21 August 1998, rain amount data were unaffected.
Actual rain amount collection dates listed under each monthly column:
May: Laate and Weekoty Fields 1997: 16 May–3 June. Weekoty Field 1998: Small single event May rain amount estimate based on weather station tipping bucket rain gage.
June: Laate and Weekoty Field 1997: 3 June–13 June. Weekoty Field 1998: Small single event June rain amount estimate based on weather station tipping bucket rain gage.
July: Laate Field 1997: 13 June–12 July and 12–23 July. Weekoty Field 1997: 13 June–12 July. Weekoty Field 1998: 20 May–11 July and 11–28 July.
August: Laate Field 1997: 23 July–8 August and 8–13 August. Weekoty Field 1997: 12 July–5 August and 5–13 August. Weekoty Field 1998: 28 July–21 August.
September: Laate and Weekoty Fields 1997: 13 August–26 September. Weekoty Field 1998: 21 August–19 September.

Table 3. Maize experiment cultivars and characteristics.

Zuni	Hybrid
Traditional, locally-adapted cultivar	1:1 mix, Pioneer Brand 3737 and 3751 varieties
Open-pollinated landrace	F1 hybrids
95–120 d maturity	100 d maturity
Blue grain, floury-flinty endosperm	Yellow grain, dent endosperm

planted at its customary depth—Zuni maize at 15 cm and Hybrid at 5 cm depth. Planting occurred May 12–13 each year.

Runoff Harvesting, and Water and Nutrient Treatments

Catchment reservoirs were installed upslope of each field to capture storm runoff that would normally flow from the watershed to the field. Reservoir capacities were approximately 53 m^3 (14,000 gallons) each. The catchments were lined with plastic sheeting to minimize seepage.

The experiment included five treatments (Table 4): precipitation-only, runoff liquid, runoff liquid and associated sediments, irrigation water to match amount and timing of applied runoff, and a treatment with more irrigation water (applied when needed to avoid crop water-deficit stress), plus nitrogen and phosphorus fertilizer. The runoff treatments were designed to test effects of different runoff components on maize productivity. To separate runoff into liquid and sediment components for treatment applications, storm runoff deposited in the catchment reservoir was allowed to settle for two to seven days after runoff events. When runoff volume from a storm event was sufficient, half of the liquid portion was transported by pipe from the catchments and applied to the runoff treatment plots, with the remaining runoff liquid and materials applied to the runoff-with-sediments treatment plots (Figure 2C). Irrigation water from district reservoirs was delivered to fields in a water truck or tanks. For the irrigation-with-fertilizer control treatment, irrigation water was applied to supply plant water needs throughout the season, and synthetic nitrogen and phosphorus fertilizers were

Table 4. Maize experiment treatments and descriptions.

Treatment	Description
Rainfed	Direct precipitation only.
Runoff	Liquid portion of runoff (water plus dissolved and suspended components).
Runoff with solids	Liquid and solid runoff components (water, solutes, sediments, and organic materials) applied to match volume and timing of the above treatment application.
Irrigation water	Irrigation water from district reservoir lakes applied to match runoff application volume and timing.
Irrigation water with fertilizer	Irrigation water from district reservoir lakes, plus synthetic N and P, applied as needed by the crop to avoid water-deficit stress. First application contained 101 kg N ha^{-1} and 36 kg P ha^{-1}; the next application added 77 kg N ha^{-1}. Seasonal fertilizer application totaled 178 kg ha^{-1} N and 36 kg ha^{-1} P.

Table 5. Total N and P contributed by applied treatments each field-year.

Field-year	Applied treatment	Events (number)	N (kg ha^{-1})	P (kg ha^{-1})
Laate 1997	Precipitation	52 (approx.)	6.92	0.37
	Runoff	4	8.10	0.71
	Runoff + Solids	4	29.58	6.48
	Irrigation	4	6.93	0.39
	Irrigation + Fertilizer	4	185.05	36.42
Weekoty 1997	Precipitation	52	2.50	0.27
	Irrigation + Fertilizer	5	180.63	36.33
Weekoty 1998	Precipitation	29	6.57	0.91
	Runoff + Solids	1	8.34	1.35
	Irrigation	1	6.59	0.91
	Irrigation + Fertilizer	2	184.75	36.92

applied during the first two irrigations in amounts recommended by New Mexico State University (Tables 4 and 5). Except for the two control treatments (precipitation-only and irrigation-with-fertilizer), treatment applications were contingent on the occurrence and volume of runoff events. The amounts and timing of these treatments varied with runoff availability each field-year.

To determine nutrient inputs of nitrogen (N) and phosphorus (P) in each treatment (Table 5), precipitation was sampled from two rain funnels at each field when precipitation amounts were measured (Table 2). Runoff, its liquid and solid components, and irrigation water were sampled after each event or application. Liquid samples (precipitation, runoff liquid portion, and irrigation water) were preserved, refrigerated, and analyzed for cation concentration (NH_4-N) by atomic absorption spectrophotometry and for anion concentration (NO_3-N and PO_4-P) by ion chromatography. Total N and P concentrations of runoff sediments were determined on fine-ground subsamples on an oven-dry basis (105 °C). Total N was determined using a Fissions EA1100 dry combustion CNSHO analyzer (Fissions Instruments, Milan, Italy). Total P was determined by the alkaline oxidation method (Dick and Tabatabai 1977).

Maize Data Collection and Analysis

Crop Density, Development, and Productivity

Crop data were collected only from the interior nine hills (subplots) of each plot to minimize border or edge effects between plots. Emergence and stages of development were monitored through flowering. Stand density was determined six weeks after planting.

Harvest occurred on October 1–2, 1997 and again on October 8–9, 1998. Plant clusters were harvested at ground level and partitioned into ears and vegetative matter and weighed in the field to measure fresh weight. The median total fresh weight subplot of each plot was collected, dried with circulating air for seven days at 60 °C, and weighed to estimate plot dry matter yields. Grain and total aboveground biomass dry-weight yields of each plot were estimated by multiplying the partitioned fresh weight of each of the plot's hills by the ratio of partitioned dry to fresh weights of that plot's subsample. Plants and grain not subsampled for dry matter determinations were made available for use by local residents.

The validity of using the median hill subsample and the ratio of dry to fresh weights of the median hill of each plot to estimate dry matter yield from fresh weights was checked by determining correlations of ear, vegetative, and total biomass between 1) fresh weights of the median hill and the mean of all nine hills within plots and 2) dry and fresh weights of the median hill within plots. Results for each field-year indicate highly positive correlations between these variables and correlation coefficients (r) of > 0.9 for all three site-years combined (Supplement A). Additionally, the shelling percentage (grain dry weight/ear dry weight) did not vary significantly. These results support the use of the median hill subsample to estimate dry matter yields.

Experimental Design and Statistical Analyses

The experiment was conducted as a generalized randomized complete block design in the two fields that were treated as blocks in an analysis of variance (ANOVA). Treatments consisted of factorial combinations of the two cultivars and five water/nutrient treatments. Within each field, treatment combinations were randomly assigned to individual plots and were replicated three times in the case of Zuni maize and twice with Hybrid maize. Plot diagrams are shown in Supplemental Figures 1A–1D.

Analyses of variance of the maize data were performed using the General Linear Models procedure of the Statistical Analysis System (SAS) version 8.01 (SAS Institute, Inc. 1999–2000) and JMP version 12 (SAS Institute, Inc. 2015). Least square means (LSMeans) of maize variables were used to adjust for the unbalanced design. Means were separated using Fisher's Least Significant Difference (LSD) test at the 0.05 probability level. In those analyses—in which cultivar x treatment interaction was evident in 2-way ANOVA—1-way ANOVA of each cultivar by treatments or both cultivars by each treatment was done. Data are reported as mean $\pm$ one standard error of the mean unless otherwise stated.

Results and Discussion

Growing Season Weather Conditions

Total growing season (May–September) rain at the Laate and Weekoty Fields was about one-third higher than the long-term Zuni average in 1997 and about 6% higher at the Weekoty Field in 1998 (WRCC 2016; Figure 3; Table 2). Most rain events were less than 5 mm (Table 2). Long-term Zuni records indicate that about 70% of summer rain occurs as minor events of less than 12.7 mm day^{-1} (Norton et al. 2007a [based on Balling and Wells 1990]; also see Benson 2010).

Summer rains began earlier than usual in 1997, with the first rain in mid-May, shortly after planting. Rain occurred frequently in the Weekoty Field during the 1997 growing season. In the 1998 season, the onset of summer rains occurred in a more typical pattern, beginning the first week of July. Overall, rain occurred less frequently in 1998 in the Weekoty Field (Table 2). Water-year precipitation prior to summer (October through May) in both 1997 and 1998 was 28% higher than average at Zuni (Benson 2010; WRCC 2016).

Early season conditions, through June, were not only drier, but also cooler in 1998 than in 1997 (Figure 4). Total Growing Degree Days (GDD) accumulated May 20 through August 21 were 800 in 1997 and 828 in 1998, fewer than the long-term average of 959 for this period (WRCC 2016). The broader season total GDD (calculated May 15 through September 26, 1997) were 1067, lower than the long-term average of 1315. These cumulative GDD are higher than those measured in experiments with traditional Southwest maize in southwestern Colorado (Bellorado 2007) and comparable to those measured in northwestern New Mexico (Adams et al. 2006). They meet the minimum GDD required for maize production in the Southwest inferred by Benson (2010), but are in the lower part of the range required by modern hybrid dent maize in the Midwest (Adams et al. 2006).

The last freezes each year occurred July 2, 1997 and June 19, 1998. Leaf tissue was damaged at both fields, but all plants survived. Although the average date of the last killing freeze is May 9 at Black Rock (WRCC 2016), later freezes are not uncommon in this region. Each field-year, the crop attained maturity before Fall killing freeze, whose average date is October 17.

Treatment Applications

Field-years differed in frequency and amount of runoff produced, resulting in differences in treatment applications (Figure 5; Table 5). In 1997, 13 of the 52 rain events generated sheet flow in bounded runoff plots in the watershed hillslopes above the Weekoty Field, but only three of these had sufficient intensity and duration to produce channel flow on the alluvial fan (Norton 2000:77–78). The first channel flow occurred in May, prior to construction of the field's catchment reservoir and the other two flows did not reach the catchment, precluding treatment applications other than the controls. The Laate Field had a similar rain pattern, but this smaller watershed produced greater and more frequent runoff flow events. The Laate catchment received flows on July 22, July 30, August 5, and August 25 in 1997, providing sufficient runoff for applications of all treatment combinations after each event. In 1998, only the August 1 rain event generated runoff that produced channel flow that collected in the catchment reservoir. The event's limited volume restricted runoff applications to only the runoff-with-solids treatment plots. Because of delayed emergence and twice the normal rain in July, fewer applications of irrigation water to the high input control treatment were required in 1998 than in 1997.

Several complex factors influence watershed runoff generation and quantities. Watershed size and threshold amounts of precipitation required to initiate runoff are briefly discussed here in the context of runoff at the maize experiment fields (see also Supplement A). The greater frequency of runoff in the Laate watershed than the Weekoty watershed likely relates to the inverse relationship between watershed size and runoff. Smaller watersheds have a greater frequency of runoff events and greater runoff yield per unit area in arid regions (Boers and Ben-Asher 1982). This was evident during our research at Zuni, where a high

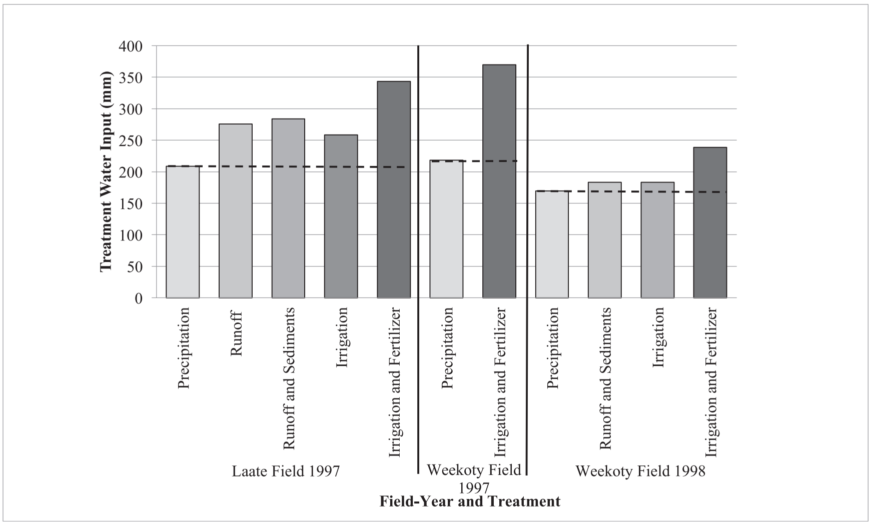

Figure 5. Seasonal total water input during each field-year. Dashed line shows precipitation contribution to total.

inverse correlation between number of runoff events and watershed area was observed in Zuni agricultural fields from 1997–1999 ($R^2 = 0.77$, $n = 8$, $p < 0.01$). In arid environments, amounts of rain needed to generate runoff vary greatly, mainly depending on factors such as watershed size, rain intensity, and rain duration. At Zuni fields, the minimum rain observed to initiate runoff was about 6–13 mm, comparable to other findings in the Southwest. Zuni farmers interviewed about their four fields reported that they usually had at least one runoff event at one field and two or three at the other fields each year (Muenchrath et al. 2002). Further data and discussion about runoff in watersheds of Zuni fields are provided in Norton (2000) and Norton et al. (2007a, 2007b).

Treatments added different amounts of nutrients to plot soils, with the two most important macronutrients, nitrogen and phosphorus, measured in this experiment (Table 5). Nitrogen inputs ranged from 2.5 kg ha^{-1} in the precipitation-only treatment to 185 kg ha^{-1} in the irrigation-with-fertilizer treatment. Phosphorus inputs ranged from < 1 kg ha^{-1} in the precipitation-only treatment to 37 kg ha^{-1} in the irrigation-with-fertilizer treatment. Nutrient inputs from runoff were fairly low, except for somewhat higher amounts in the runoff-with-solids treatment at the Laate Field. Generally, soil fertility and nutrient levels were probably not limiting factors for maize production in this experiment. No visual symptoms of nutrient deficiencies in the maize were observed in either field and levels of N and P in the leaves and grain compared with well-fertilized maize in the Midwest current fields also indicated sufficient soil fertility (Cerrato and Blackmer 1990, 1991; Mallarino et al. 1991; Sandor et al. 2007). Adequate fertility in the experiment soils may be partly due to the traditional fields having been fallow for a number of years before the experiment. In contrast, during a greenhouse experiment growing a traditional Southwest maize (Chapalote) in samples of prehistoric agricultural soils under different nutrient treatments, early maize growth was greatly increased with added nitrogen (Sandor and Gersper 1988).

Amounts of solids (mineral sediment and organic matter) added in the runoff treatments varied greatly. Runoff water applied to the Laate Field in 1997 contained an average of 1.0 g L^{-1} dry weight of suspended solids, whereas the runoff-with-solids treatment added 524 g L^{-1} dry weight of solid materials, mostly in the form of a slurry that settled at the bottom of the catchment reservoir. In contrast, the 1998 Weekoty application of runoff-with-solids contained only 6.8 g L^{-1} dry weight of solid materials, reflecting differences in runoff events and field watershed sizes and characteristics (Norton 2000). Studies of runoff and nutrient transport in Zuni watersheds, including those above the maize experiment fields, indicate that organic materials and sediment transported with runoff are a critical process for soil-building and nutrient replenishment of Zuni traditional fields (Norton et al. 2003, 2007a, 2007b; Sandor et al. 2007). The nutrient composition of maize grown in the experiment—and relationship of soils, runoff, and maize nutrients—will be covered in another paper. One finding relevant to nutritional quality is that the Zuni maize had a higher grain nitrogen content and a higher proportion of nitrogen in the grain than the leaf, compared with Hybrid maize (Sandor et al. 2007). This suggests that the Zuni maize has a higher protein content and an ability to mobilize a greater proportion of nitrogen to its grain.

Maize Emergence, Population Density, and Development

Maize emergence and stand density differed substantially between the two years at the Weekoty Field (Table 6). The cooler and drier early season conditions in 1998 delayed emergence and reduced plant stand densities relative to 1997. In 1998, 20% of Zuni plots, and 40% of Hybrid plots, failed to attain 50% emergence within six weeks of planting. Of those plots that did reach 50% emergence or more, emergence required about one week longer than in 1997. Days-to-emergence did not differ between cultivars. Emergence and stand density were similar between fields in 1997. Each field-year, Zuni maize had a lower emergence percentage and mean plant population density than the Hybrid maize. The Zuni maize emergence percentage is consistent with that observed in Zuni farmers' fields, where only 30–60% of planted seed emerged successfully in 1998 (Muenchrath et al. 2002). Both years, Zuni cultivar stand densities were similar to the better stands documented in Zuni farmers' fields.

Because Zuni springs are ordinarily dry and windy, Zuni maize is traditionally sown at 15 cm or greater depth primarily to place seed in zones of adequate soil moisture (Muenchrath et al. 2002). The greater planting depth apparently provides no advantage when spring soil moisture is not limiting, as occurred in 1997. Under dry conditions in May and June 1998, emergence was less reduced in Zuni than in Hybrid maize, presumably because moisture was more limiting nearer the soil surface where Hybrid seed was sown. In 1998, the precipitation-only and irrigation (to extent of runoff) treatment had a significantly lower mean population density than did the irrigation-plus-fertilizer treatment, indicating that moisture limited emergence. However, the precipitation-only treatment also had lower population density than the runoff-plus-solids

Table 6. Mean (least square means ± standard error) emergence and plant population density, by field-year and cultivar.

		Emergence		Plant population density	
Field-year	**Cultivar**	(Days after planting)	(%)	(plants hill^{-1})	(plants ha^{-1})
Laate 1997	Zuni	12.9±0.5 NS	54.4±1.8 ****	3.2±0.1 ****	14,058±536 ****
	Hybrid	12.6±0.6	90.0±2.2	5.3±0.1	23,605±657
Weekoty 1997	Zuni	13.2±0.5 NS	58.5±2.3 ****	3.4±0.2 ****	14,979±678 ****
	Hybrid	13.1±0.7	90.6±2.9	5.4±0.2	24,074±831
Weekoty 1998	Zuni	20.0±1.9 NS	49.6±2.4 **	3.0±0.1 **	13,025±658 ***
	Hybrid	18.3±2.4	61.7±3.0	3.7±0.2	16,512±806

, *, **** Significant difference between cultivars at the 0.01, 0.001, and ≥ 0.0001 probability levels, respectively, by *t* test. NS indicates no significant difference between cultivars.
Sampling units: for Emergence (Days after planting) the sampling unit is the plot. For the other variables, the sampling unit is the hill/subplot.

treatment, which cannot be explained by moisture because runoff did not occur until August, after plant population density was measured. Emergence results parallel those of plant population density.

Zuni and Hybrid maize developed at similar rates, with no significant cultivar differences in timing of anthesis (pollen shed) or silk emergence in either year or site. Mean 50% silk emergence was attained 97 days after planting and in 794 GDD in 1997 and 95 days and 725 GDD in 1998. In 1997 at both fields, mean 50% silk emergence occurred earlier in the irrigation-plus-fertilizer treatment (91–92 days and 745–755 GDD) than in the other treatments (98–100 days and 809–821 GDD), indicating that the higher water and possibly nutrient inputs increased maize growth rates. The Zuni maize required about 130 days from planting to reach maturity in both this study in 1998 and in another experiment in northwestern New Mexico in 2004 (Adams et al. 2006:68).

Insect and other animal predation of seedlings occurred to a limited extent each field-year. Ants were the main predators, reducing plant population in some plots. Ants were not disturbed due to cultural reasons; a few subplots were shifted slightly away from ant colonies. In 1997, maize stands on a hill (subplot) basis were reduced 5% by predation in the Laate Field and 4% in the Weekoty Field. In 1998, predation reduced maize stands 9% in the Weekoty Field. Predation from ants and especially other animals also caused damage to maize in other experiments with traditional maize in the Southwest (e.g., Bellorado 2007). Both years, two adjacent plots in the Weekoty Field, one Zuni and one Hybrid, exhibited lower densities and stunted plants. Although numerous factors were examined, no cause for the poor stands or stunting in these plots was ascertained.

Maize Yield and Productivity

Maize grain yields and biomass production differed especially by year, cultivar, and treatment (Figures 6 and 7; Table 7). Grain yield on both a per plant and land area basis within each kind of maize were similar between fields in 1997 (Table 7). The overall 1997 field mean (Table 7) is lower in the Weekoty Field than the Laate Field because runoff events in the smaller Laate watershed allowed all treatments to be applied, whereas the lack of an alluvial fan runoff event in the

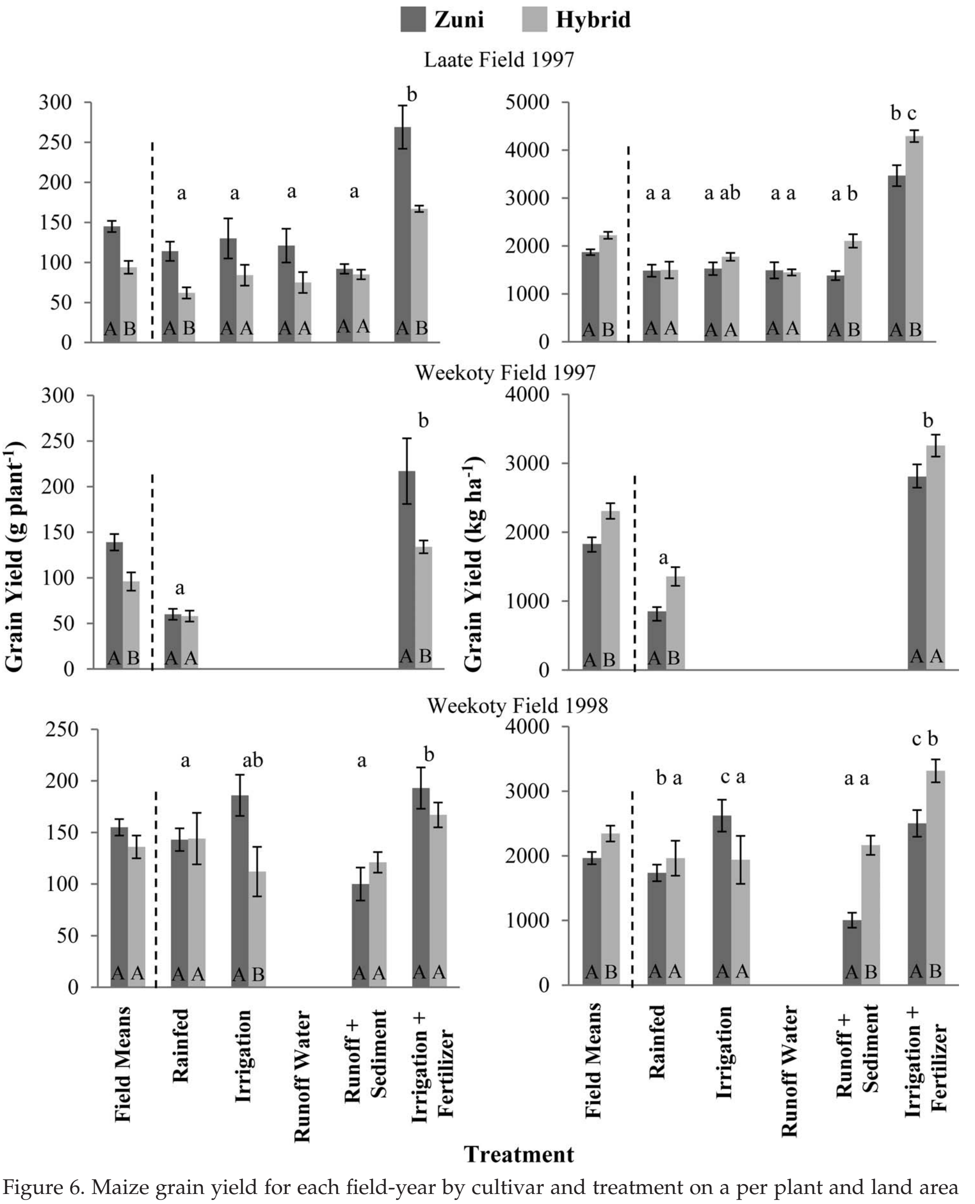

Figure 6. Maize grain yield for each field-year by cultivar and treatment on a per plant and land area basis. Data are means with error bars showing ± 1 standard error of the mean. Field means by cultivar are least square means. Different uppercase letters indicate significant difference between cultivars within a treatment at the < 0.05 probability level. Different lowercase letters indicate significant differences among treatments across cultivars at the < 0.05 probability level. In those analyses in which a cultivar x treatment interaction was found in 2-way ANOVA, lower case letters for each cultivar x treatment are shown, based on 1-way ANOVA.

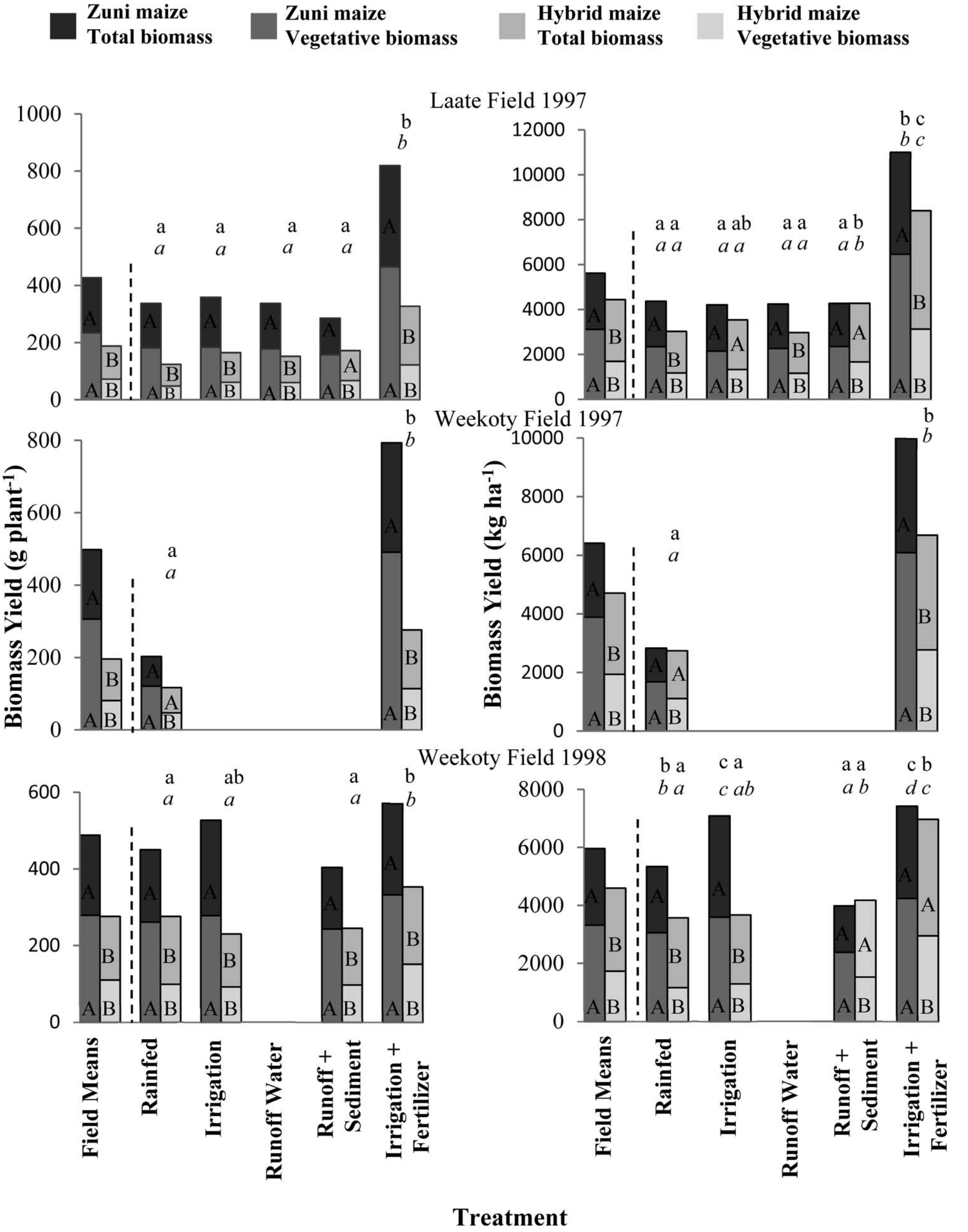

Figure 7. Maize total and vegetative dry weight biomass means for each field-year by cultivar and treatment on a per plant and land area basis. Field means by cultivar are least square means. Different uppercase letters indicate significant difference between cultivars within a treatment at the < 0.05 probability level. Different lowercase letters indicate significant differences among treatments across cultivars at the < 0.05 probability level (vegetative biomass in italics and total biomass in regular lowercase letters). In those analyses in which a cultivar x treatment interaction was found in 2-way ANOVA, lower case letters for each cultivar x treatment are shown, based on 1-way ANOVA.

Table 7. Mean (± standard error) grain yield and ears per plant by field-year and cultivar. Means by cultivar are least square means; field mean is the actual mean.

Field-year	Cultivar	Grain yield (g plant^{-1})	Grain yield (kg ha^{-1})	Ears per plant (number plant^{-1})
Laate 1997	Zuni	145±7 ***	1870±60 ***	2.3±0.1 ****
	Hybrid	94±8	2223±72	1.5±0.1
	Field Mean	121±7	1981±77	2.0±0.1
Weekoty 1997	Zuni	139±9 **	1830±97 **	2.5±0.1 ****
	Hybrid	96±10	2308±113	1.3±0.2
	Field Mean	83±6	1433±80	1.5±0.1
Weekoty 1998	Zuni	155±8 NS	1965±95 *	2.4±0.1 ***
	Hybrid	136±11	2344±122	1.7±0.2
	Field Mean	148±7	2073±83	2.1±0.1

*, **, ***, **** Significant difference between cultivars at the 0.05, 0.01, 0.001, and ≤ 0.0001 probability levels, respectively, by *t* test. NS indicates no significant difference between cultivars.

larger Weekoty watershed precluded runoff and irrigation (to extent of runoff) treatments, so that those plots reverted to a precipitation-only treatment. This also explains why the overall 1997 Weekoty Field mean in Table 7 is lower than for the means calculated by cultivar (LS mean, i.e., the mean of treatment means). Yield at the Weekoty Field was greater in 1998 than 1997, partly because a runoff event allowed the runoff and irrigation treatments. However, the precipitation-only plots at the Weekoty Field also had higher yields in 1998 than in 1997, which may be partly due to higher mid-summer (July–August) precipitation in 1998. Sufficient water during maize silking is especially critical for grain production (Muenchrath and Salvador 1995; Shaw 1988).

Zuni maize grain yield per plant was significantly greater than Hybrid yield in 1997 at both fields, but grain yield per plant did not differ between cultivars in 1998 (Figure 6; Table 7). The greater Zuni yield per plant is mainly attributed to its ear prolificacy (Table 7). However, Zuni maize ear number per plant was greater than Hybrid in both years, so other factors, such as lower plant population density, must have also influenced grain yield per plant (Olson and Sander 1988; Table 6). Even higher grain yield per plant (355 g plant^{-1}) and ears per plant (2.8) were reported for the same Zuni maize grown under optimal irrigation and nutrient conditions in northwestern New Mexico (Adams et al. 2006:51). Grain yield on a per plant basis is an important measure of potential productivity because the amount of land that could be cultivated has not been a limiting factor at Zuni.

On a land area basis, however, Hybrid maize produced more grain than Zuni maize both field-years, reflecting the higher population density of Hybrid maize (Table 6). Yields per land area are commonly lower in traditional landrace cultivars compared with hybrid maize (Muenchrath et al. 2002:25). Hybrid maize yields were lower than expected for modern F1 hybrid dents, likely due to two factors. First, the Hybrid maize population densities in the experiment (overall mean of 17,000–24,000 plants ha^{-1}; see Table 6) were far less than those used in commercial maize production, which are well over 50,000 plants ha^{-1} in the Corn Belt (U.S. Department of Agriculture, National Agricultural Statistics Service

[USDA-NASS] 2016). Second, even in the irrigation-with-fertilization treatment, total water application was less than required for maximum production. Other factors may also be involved, such as not using pesticides or controlling for ant predation.

To evaluate maize production in a larger context, yields in this experiment are compared with those from other traditional fields, experiments with traditional maize, and current commercial production (see Supplement A). The non-irrigated (precipitation-only or with runoff) Zuni maize yields in this experiment, averaging 852–1736 kg ha^{-1} for the three site-years, are mostly higher than those documented in traditional farmers' fields at Zuni and other Southwestern traditional fields, which commonly average 400–900 kg ha^{-1}. Yields of about 500–629 kg ha^{-1} have been estimated in modeling prehistoric maize production in relation to climate in the Mesa Verde region (Benson 2010; Kohler 2012). Compared with mean Zuni maize yields in the irrigation-with-fertilizer treatment in this experiment (2501–3467 kg ha^{-1}), yields of irrigated maize in traditional farmers' fields in the Southwest range from about 630–2590 kg ha^{-1}.

Relative to yields from other Southwestern maize experiments, the Zuni maize experiment yields are in a similar overall range. In an experiment growing Navajo maize north of Zuni (Hubbell and Gardner 1950), yields averaged 1145 kg ha^{-1} with rain alone (range 214–2704 kg ha^{-1}) and two to three times higher with runoff and irrigation. Yields for a number of traditional Southwest cultivars grown in northwestern New Mexico with optimal irrigation and nutrient inputs ranged from about 1840–3300 kg ha^{-1} (Adams et al. 2006).

Prior to the 1930s and the adoption of hybrid maize, United States maize yields averaged about 1300 kg ha^{-1}. Current commercial maize yields in the United States Midwest (also irrigated maize in New Mexico and Arizona) average over 10,000 kg ha^{-1}, with intensive management and high plant population densities (USDA-NASS 2016).

Vegetative and total biomass productivity was greater in the Zuni cultivar than Hybrid maize each field-year (Figure 7). The greater vegetative biomass of the Zuni cultivar is attributed to its tendency to tiller (development of additional stems; compare Figure 2D, E). The biomass differences between cultivars are reflected in the Harvest Index (HI), the ratio of grain dry weight to total biomass dry weight. The HI of the Zuni maize is significantly lower than that of Hybrid maize (0.3 vs. 0.5 for all site-years, significant at $p < 0.001$) because the Zuni maize has a lower grain yield but higher biomass per unit area. Hybrid maize HI of 0.5 is typical for modern commercial hybrid maize (Ciampitti and Vyn 2012). Possible advantages of tillering and a more vegetative and "bushy" plant structure—as well as growing multiple plants in clusters, common in traditional maize in arid lands like the Southwest—include a more shaded and cooler microclimate, greater physical stability to withstand wind or runoff, protection of ears against predators, and increased yield stability (Muenchrath and Salvador 1995).

Differences in grain and biomass yield by treatment in both cultivars were mostly dominated by the irrigation-with-fertilizer treatment (Figures 6 and 7). The irrigation-with-fertilizer treatment produced far more grain and biomass on a per plant and per land area basis than other treatments in 1997 at both fields. In 1998, grain yields were greatest in the irrigation (to extent of runoff) and irrigation-with-fertilizer treatments. Total biomass production varied among treatments in 1998; irrigation-with-fertilizer produced more vegetative biomass than the other treatments. Yield trends among treatments are tentatively attributed to the effects of water amounts and timing rather than nutrient inputs, as previously discussed. Overall, there is a weak but significant positive correlation between yield and water input ($r = 0.38$, $p < 0.0001$ for all subplots; $r = 0.54$, $p = 0.09$ by treatment for all field-years), although this mainly corresponds to the higher input irrigation treatment in relation to all other treatments. In the Pueblo Farming Project maize experiment in southwestern Colorado, a higher correlation ($r = 0.81$) between maize yield and precipitation was measured (Varien and Bocinsky 2016).

A key finding in this experiment is that maize was produced in all three site-years in the precipitation-only treatment. It has been thought that rainfed maize production is generally not feasible in the arid to semiarid Southwest with its relatively low precipitation and that some supplemental water is usually needed (e.g., Kintigh 1985; Rhode 1995; see discussion in Dominguez and Kolm 2005; Sandor and Homburg 2015). This also brings up the question about minimum water requirements for maize in the Southwest. Fifteen centimeters of summer precipitation is commonly given as the minimum needed (e.g., Benson 2010; Shaw 1988). That minimum was met in both years of the experiment, with about 17–19 cm of summer precipitation (June–September; Figure 5; Table 4). In reviewing climate records for Zuni (1949–2008), Benson (2010) found that annual and growing season precipitation required for growing maize is deficient about half the time. Although Southwestern traditional maize is highly variable and remains understudied, there are important differences in genetics, physiology, and management from modern hybrid maize (Adams 2015). Yet both Zuni and Hybrid maize in this experiment produced reasonable yields on precipitation alone. Nevertheless, some traditional Southwest maize cultivars seem more adapted to arid conditions; for example, with the ability to be planted deeper and to have more extensive root systems (Bousselot et al. 2017). More research is needed on this important question of Southwest maize adaptation (Adams 2015).

An important question from the experiment is why the runoff treatments did not result in higher yields (Figure 6). In both the 1997 Laate Field and 1998 Weekoty Field that received runoff treatments, grain yields were not significantly different than the precipitation-only treatment. In the 1998 Weekoty Field, the irrigation treatment (to extent of runoff) had a higher yield on the land area basis than the runoff treatment. Reasons for these results are uncertain, but some possible factors relate to treatment method, experiment duration, and weather conditions. Perhaps runoff water input was not enough of an increase over precipitation to affect yield, given precipitation was sufficient to produce maize (Figure 5). Among all treatments excluding the higher input irrigation treatment (i.e., precipitation-only, runoff, and limited irrigation), the correlation between water input and yield is very weak or absent. Another possibility is that the one-year duration of the runoff treatments was not sufficient for the organic matter in the runoff solids to mineralize and contribute nutrients available to the maize.

The higher yield in the 1998 irrigation-only treatment compared with the runoff treatment suggests suppression of available nutrients like nitrogen. However, this is contradicted by the sufficient levels of N and P in maize leaves and grain. It is also possible that the artificial (separation of water and solids) application of runoff sediments in 1997 had a negative effect on the maize. In a five-year experiment with Navajo maize north of Zuni, excessive runoff water and sediment decreased maize yield, but smaller additions of runoff water and sediment (yet larger than inputs in this experiment) increased yield by two to three times over yields in rain-only treatments (Hubbell and Gardner 1950). Other research emphasizes the long-term value of runoff in increasing crop productivity by adding supplemental water, replenishing nutrients, and building soils (Norton et al. 2007a, 2007b).

Conclusions

Conclusions from the main findings of this maize experiment in traditional Zuni fields are:

- Maize grain was produced both years from all water and nutrient treatments, including the precipitation-only treatment without supplemental water or nutrients. Maize agriculture is possible in this semiarid environment without supplemental water in years with at least average precipitation.
- Maize production was generally much higher in the irrigation-with-fertilizer treatment compared with precipitation-only and runoff treatments, which were mostly similar. Compared with commercial Hybrid maize, which had a higher plant population density, Zuni blue maize yields were lower on a land area basis (kg ha^{-1}). However, Zuni maize produced greater yields per plant (g $plant^{-1}$) than Hybrid maize. The Zuni maize generally also produced more biomass than Hybrid maize, which imparts advantages such as a cooler and effectively moister microclimate, physical protection, and yield stability (Muenchrath and Salvador 1995). Traditional deeper planting of Zuni maize seed enabled it to be less reduced in emergence and plant population density relative to Hybrid maize during the dry months of May and June 1998. Overall, maize yields were as high or higher compared with yields of Southwest traditional maize reported in ethnographic literature and other traditional maize experiments.
- Productivity differences among treatments are mainly attributed to differences in water inputs rather than nutrients. Although the amount of water applied in the irrigation-with-fertilizer treatment was greater than that applied in the other treatments, it was less than what is usually available for commercial maize production (about 50–60 cm of water; Olson and Sander 1988). Reasons for the lack of positive response of maize production to supplemental water and nutrient inputs from runoff is uncertain. Factors may include the limited number of runoff events for treatment applications and amounts of runoff actually applied, the extended fallow periods and existing soil nutrient content

preceding the experiment, and the short duration of the experiment in terms of runoff inputs (one year per field).

The results of the experiment and uncertainties discussed point to the need for expanded quantitative research of ancient and traditional agriculture through scientific crop experiments, as advocated by other researchers (Adams 2015; Bellorado 2007). A combination of multidisciplinary observational studies and longer-term controlled experiments of five years or more is recommended to better assess long-term effects of runoff and its components on crop productivity. This would allow improved assessment of the effects of water on productivity across a wider range of water input amounts and timing from precipitation and runoff in relation to maize development and production. Experiments over longer time periods would also provide precipitation, temperature, and other data for a greater range of climate conditions influencing crop production. Incorporating a range of crops and crop management practices such as intercropping into experiments is also needed. Partnering with traditional farmers in crop experiments was beneficial in this study and others (e.g., Varien and Bocinsky 2016) and should continue to be a priority in future studies.

An important distinction is that production goals generally differ between traditional subsistence farming and large-scale commercial crop production. The priority in most commercial crop production is maximum yield achieved partly through high water and nutrient inputs, whereas the emphasis in lower-input traditional agricultural systems is more on long-term yield stability (Adams 2015:39; Muenchrath and Salvador 1995). In traditional societies that have lived on the same land for many generations, dependable, sustainable production that conserves land and water resources is essential (Sandor et al. 2006).

Many traditional crops are time-tested and adapted to the arid, variable environments increasingly prevalent today with climate change (Nabhan 2013). These crops contain diverse germplasm that is important in developing cultivars to respond to climate and other environmental changes and to head off problems associated with a narrow genetic range, such as vulnerability to diseases and pests. Yet in many cases, little is known about the genetics and physiology of traditional crops—a good example being the many landraces of open-pollinated maize in the Southwest (Adams 2015). Besides the crops themselves, traditional peoples in arid environments have developed management and conservation strategies, such as runoff agriculture, that provide supplemental water and regenerate nutrients and soil without the use of conventional irrigation and fertilization. Traditional crops, management practices, and underlying knowledge and experience offer valuable insights about how to farm in arid, spatially and temporally variable climate conditions over long time periods.

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