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COMPARING MAIZE PALEOPRODUCTION MODELS WITH EXPERIMENTAL DATA

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*In agrarian societies, such as the ancestral Pueblo of the Four Corners region of the US Southwest (c. AD 600–1300), the resilience of crops in the face of climate challenges was of paramount concern. Consequently, students of these societies have invested much effort in modeling the response of traditional crops to ancient weather patterns. Less effort has been made to evaluate the quality of those reconstructions with experimental studies. Here, we report on results from the Pueblo Farming Project (PFP), a long-term collaboration between the Crow Canyon Archaeological Center and the Hopi tribe. From 2009 through 2015, PFP researchers and members of the Hopi tribe planted four experimental gardens of Hopi maize (*Zea mays*) on Crow Canyon's campus in southwestern Colorado using traditional methods. PFP researchers recorded growth progress over the growing season, harvested the corn, measured characteristics of the resulting crop, and derived yield estimates. We present the results of the garden experiments and we compare experimental yields with computational estimates of potential maize yield developed by the Village Ecodynamics Project (VEP). We find that Hopi maize flourishes in this part of the Hopi ancestral land and that PFP experimental yields are highly correlated with VEP yield estimates. We suggest that these PFP data may be used to refine existing maize paleoproductivity estimates, and we propose future directions for farming experiments in the Four Corners.*

Keywords *Ancestral Pueblo, Hopi, maize agriculture, experimental farming, crop modeling*

Introduction

It would be impossible to overstate the importance of maize (*Zea mays*) to Pueblo people of the southwest United States (SWUS). Indeed, for archaeologists, it is the introduction of maize agriculture that marks the beginning of Pueblo society. A set of material remains and cultural practices accompany the initial appearance of maize and we can trace the changes in this archaeological culture from these beginnings to the present day (Geib et al. 2017). Similarly, the traditional knowledge of Pueblo people recounts how their origins are tied to maize and the adoption of agriculture as the primary mode of subsistence (Wall and Masayesva 2004). Given the central role of maize in Pueblo society past and present, understanding the productivity of maize farming is of paramount importance to reconstructing Pueblo history and explaining how and why Pueblo culture changed.

Maize was the most important food source for ancestral Pueblo people, even though their subsistence economy included cultivating other crops, hunting game, and gathering wild plants. Isotopic analyses of skeletal remains and hair

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document an early and consistent dependence on maize showing that, by at least 200 BC, maize minimally comprised 70% of the calories consumed by Pueblo people (Coltrain and Janetski 2013; Cooper et al. 2016; Matson 2016). Early dependence on maize is further supported by analyses of coprolites (Aasen 1984; Androy 2003; Nott 2010), macrobotanical remains (Geib 2011), and settlement patterns (Geib 2011; Matson 1991). The fact that multiple, independent lines of evidence document the early and continued dependence on maize by Pueblo people strengthens this inference and underscores the importance of estimating maize paleoproductivity.

Maize is also central to Pueblo ceremonial and cultural life (Wall and Masayesva 2004). Maize is woven into the tapestry of Pueblo life metaphorically (Washburn 2012) and materially by being integral to rites that mark childbirth and the naming of babies, initiations that signal the transition from childhood to adulthood, and the transition that marks the end of life. It is also incorporated into many Pueblo ceremonies and communal feasts that occur alongside these ceremonies. The use of maize in these contexts is important because it creates a network of social relationships that extend beyond the family and thereby increases the social, demographic, and political scale of individual networks and collective societies. Potter and Ortman (2004:175) suggest that Pueblo communal feasts were a metaphorical extension of the domestic meal and, in this way, Pueblo feasts differ from feasting contexts in other parts of the world (Varien et al. 2017). Potter and Ortman (2004) further argue that maize became more important at communal feasts through time as hunted resources were depleted and was especially important at ceremonies in the large thirteenth-century villages of the Mesa Verde region of southwestern Colorado. The central role that maize plays in Pueblo social and ceremonial life means that estimating paleoproductivity is not only key to reconstructing Pueblo subsistence, but also to understanding Pueblo social and political organization.

Many studies link either shortfalls or abundance in maize yields to important events in Pueblo history. There is a connection between food scarcity and warfare in human society in general (VanDerwarker and Wilson 2015) and in Pueblo society in particular (Kohler et al. 2014; Kuckelman 2016; LeBlanc 1999). Episodes of drought are assumed to lead to food scarcity that is often accompanied by conflict and violence and these are linked to the depopulation of localities and regions (Benson and Berry 2009; Bocinsky and Kohler 2014; Kuckelman 2010a, 2010b; Schwindt et al. 2016). In contrast, abundant moisture is assumed to lead to food surplus and these periods have been linked to the expansion of sites and polities (Bocinsky et al. 2016; Wills and Dorshow 2012).

Clearly, we need precise estimates of maize productivity if we are to understand the development of Pueblo society. These estimates need to go beyond coarse-grained analyses that identify periods of scarcity and abundance for large regions. Instead, we need fine-grained estimates of maize production that measure annual changes in maize harvests at the scale of individual Pueblo farms across a landscape that varied in its productive potential. Furthermore, these estimates, where available, must be grounded in (or at least confronted with) empirical evidence of maize yields grown using traditional cultivation techniques. We present the framework of such a reconstruction here by comparing computational estimates of potential maize yield developed by the Village Ecodynamics Project (VEP) (Kohler 2012; Kohler and Varien 2012) with the results of an experimental farming initiative known as the Pueblo Farming Project (PFP).

Productivity Modeling in the Northern Southwest

Archaeologists in the SWUS have been interested in the effects of climate on agricultural productivity for almost a century (Douglass 1929). Early dendroclimatologists focused on identifying periods of drought in tree-ring chronologies and connecting them with cultural shifts in the archaeological record, for example the "Great Drought" of AD 1276–1299 and the depopulation of the central Mesa Verde (CMV) region by ancestral Pueblo farmers during that period (Douglass 1929:751, 766). Dean and colleagues (Cordell et al. 2007; Dean 1988, 1996; Dean and Van West 2002) continued to explore evidence for the impact of regional droughts on ancestral Pueblo populations. Benson et al. (2007:205) corroborate these claims and suggest that large droughts in the mid-twelfth and late-thirteenth centuries were primarily characterized by reductions in summer monsoonal moisture that would have had devastating effects on crop yields. These studies note that joint reconstructions of potential maize yields and demography are crucial for connecting drought to human behavior (Kohler 2010:103).

Correlation-based Yield Reconstructions

The tree-ring-based studies above are founded on the hypothesis that reduced precipitation generally resulted in lower maize yields regionally, though studies are not specific in where or to what extent those reductions might have impacted maize. Over the last three decades, archaeologists in southwestern Colorado have developed methods for modeling potential maize yield in the past via correlation-based analyses relating contemporary production records to modern climate and tree-ring chronologies (Burns 1983; Kohler 2012; Van West 1994). Here, we summarize these primary efforts in the CMV and pay particular attention to changes in model sophistication and complexity through time (Figures 1–3). Kohler (2010:105–109) provides a thorough technical review of efforts by Burns (1983), Van West (1994), and the VEP (see also Kohler 2012) and readers interested in the details of the reconstructions (such as calibration data, correlation statistics, etc.) are encouraged to consult Kohler (2010) and the original studies.

Burns (1983) presented the first annual-scale reconstruction for southwestern Colorado that directly correlated historic maize yields with several regional tree-ring chronologies (Figure 1). He analyzed historical maize yield data from Archuleta, Montezuma, La Plata, San Miguel, and Dolores counties in Colorado collected between 1926 and 1960 (Burns 1983:307–311)[1]. Burns first removed a "technology trend" from the historic yield data by controlling for pounds of fertilizer per harvested acre as a proxy for all technological innovation trends

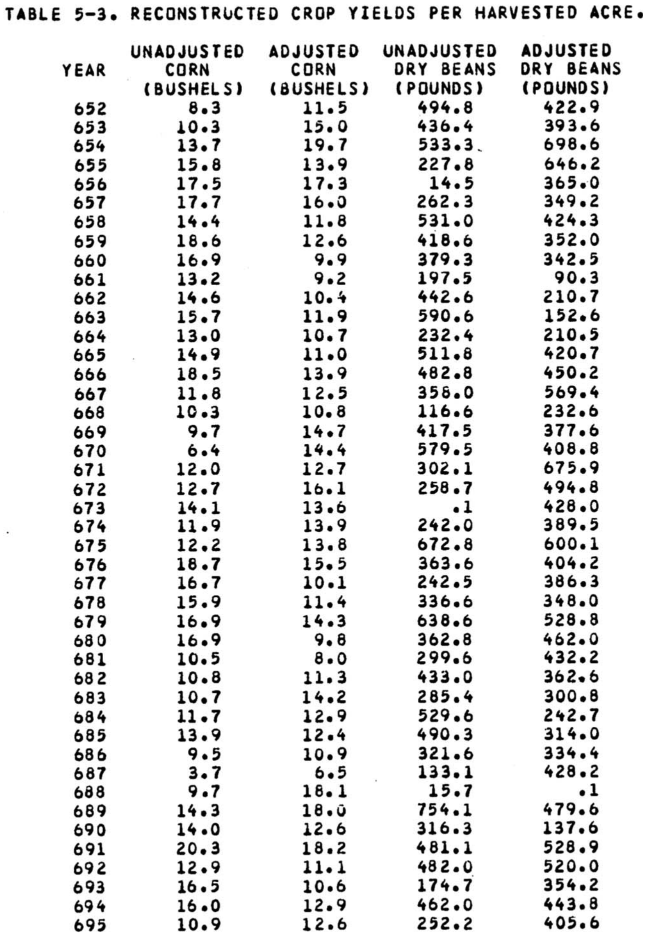

TABLE 5-3. RECONSTRUCTED CROP YIELDS PER HARVESTED ACRE.

YEAR	UNADJUSTED CORN (BUSHELS)	ADJUSTED CORN (BUSHELS)	UNADJUSTED DRY BEANS (POUNDS)	ADJUSTED DRY BEANS (POUNDS)
652	8.3	11.5	494.8	422.9
653	10.3	15.0	436.4	393.6
654	13.7	19.7	533.3	698.6
655	15.8	13.9	227.8	646.2
656	17.5	17.3	14.5	365.0
657	17.7	16.0	262.3	349.2
658	14.4	11.8	531.0	424.3
659	18.6	12.6	418.6	352.0
660	16.9	9.9	379.3	342.5
661	13.2	9.2	197.5	90.3
662	14.6	10.4	442.6	210.7
663	15.7	11.9	590.6	152.6
664	13.0	10.7	232.4	210.5
665	14.9	11.0	511.8	420.7
666	18.5	13.9	482.8	450.2
667	11.8	12.5	358.0	569.4
668	10.3	10.8	116.6	232.6
669	9.7	14.7	417.5	377.6
670	6.4	14.4	579.5	408.8
671	12.0	12.7	302.1	675.9
672	12.7	16.1	258.7	494.8
673	14.1	13.6	.1	428.0
674	11.9	13.9	242.0	389.5
675	12.2	13.8	672.8	600.1
676	18.7	15.5	363.6	404.2
677	16.7	10.1	242.5	386.3
678	15.9	11.4	336.6	348.0
679	16.9	14.3	638.6	528.8
680	16.9	9.8	362.8	462.0
681	10.5	8.0	299.6	432.2
682	10.8	11.3	433.0	362.6
683	10.7	14.2	285.4	300.8
684	11.7	12.9	529.6	242.7
685	13.9	12.4	490.3	314.0
686	9.5	10.9	321.6	334.4
687	3.7	6.5	133.1	428.2
688	9.7	18.1	15.7	.1
689	14.3	18.0	754.1	479.6
690	14.0	12.6	316.3	137.6
691	20.3	18.2	481.1	528.9
692	12.9	11.1	482.0	520.0
693	16.5	10.6	174.7	354.2
694	16.0	12.9	462.0	443.8
695	10.9	12.6	252.2	405.6

Figure 1. Paleoproductivity data as presented in Burns (1983). Burns, working in the late 1970s and early 1980s, did not have the capacity to easily represent his reconstructions graphically. In fact, there were three figures in his entire 805-page dissertation. All of his statistical calculations were coded in Fortran 77 and were run on paper punch cards at the University of Arizona. Burns and Malcolm Cleaveland wrote the computer program "FOOD," which is fully reproduced as Appendix 8 in Burns' dissertation. This figure is a scan of Burns (1983:Table 5.3) for AD 652–695.

(Burns 1983:Chapter 5). Critically, Burns only applied the trend adjustment to years when the fertilizer record trended with the yield data, resulting in a reduction of the bean yields for 34 of his 35 calibration years (Burns 1983:82, 84). Burns then experimented with regressing the corrected maize-yield data on several regional tree-ring chronologies, including lagged versions of the series. After settling on five regional chronologies, Burns generated a productivity reconstruction from AD 652 to 1968. Because of the relatively short calibration period used, Burns was unable to validate his predictions against any productivity data not used for calibration.

Van West (1994:97–102) spatialized Burns' reconstruction by correlating a trend-adjusted version of Burns' modern yields (from AD 1931–1960 for

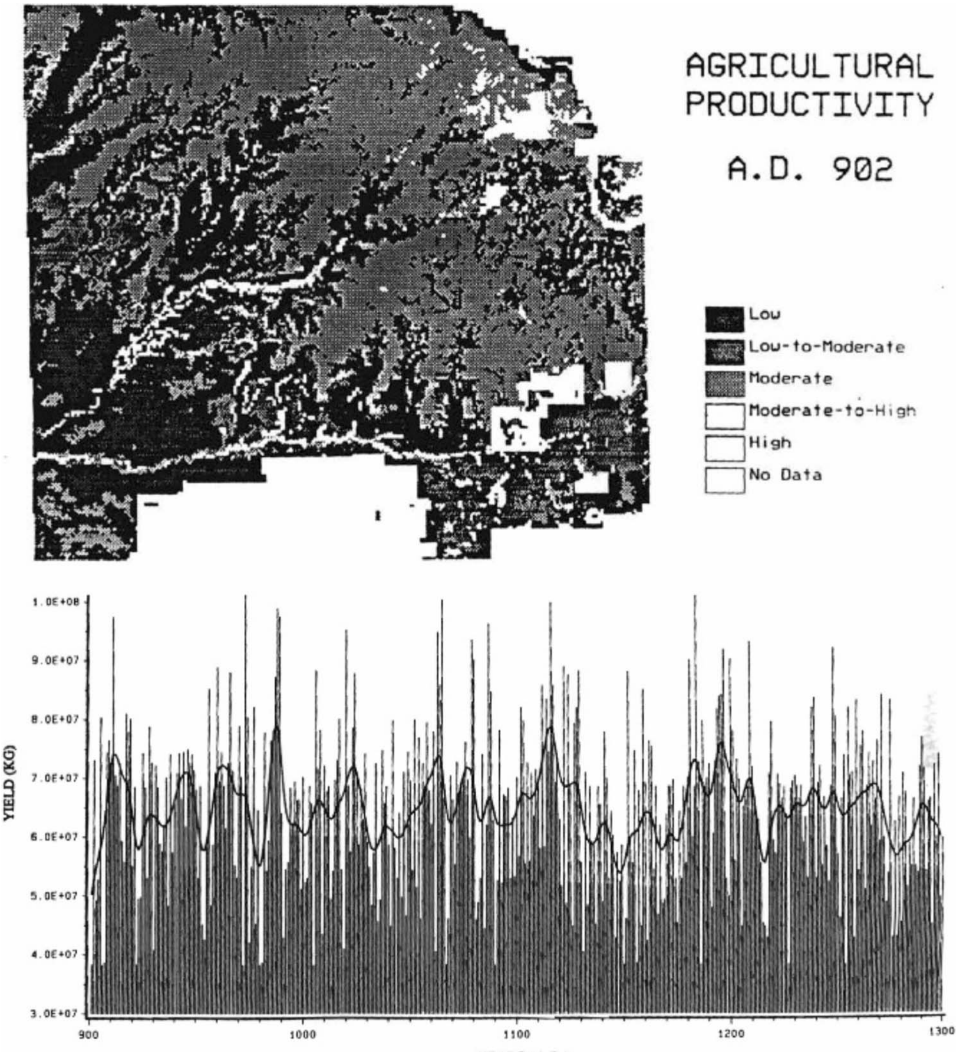

Figure 2. Paleoproductivity data as presented in Van West (1994). Van West, working at Washington State University, had access to state-of-the-art computing facilities for the time, including the early geographic information systems VICAR/IBIS (which operated on a mainframe) and EPPL7 (which was on a desktop computer, then called a "microcomputer"). VICAR continues to be developed, maintained, and used at NASA's Jet Propulsion Laboratory. EPPL7 is a raster GIS back-end still used in the EPIC GIS system developed by the state of Minnesota. Van West created color graphics that could at that time only be presented on computer screens; all the figures in her dissertation and subsequent publication (Van West 1994) were formatted for b/w dot-matrix printers. Adapted from Van West (1994:Figure 4.3, Figure 5.1).

Montezuma county only) with a spatial reconstruction of regional Palmer Drought Severity Index (PDSI) (Palmer 1965; Wells et al. 2004) values calculated from contemporary regional soils data (Van West 1994:55–94; Figure 2). The PDSI is a monthly measure of stored soil moisture available for plant growth; it is a

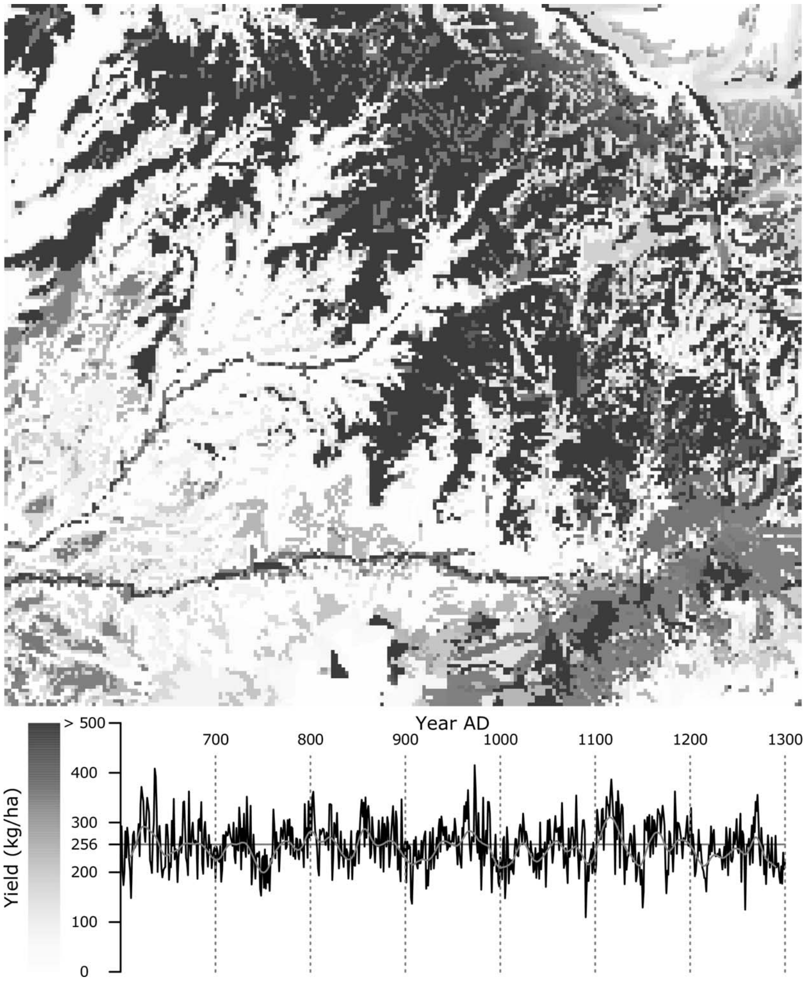

Figure 3. Paleoproductivity data used in the VEP (Kohler 2012). Bocinsky automated elements of the VEP I paleoproductivity reconstruction method (Kohler 2012) by scripting it in the *R* programming language (see Note 11). The black line in the graph is the average yield across the study area, through time. The thicker line smooths the yield using a 21-year, center-aligned Gaussian filter with a 5-year standard deviation.

function of soil depth, texture, available water-holding capacity, precipitation history, and changes in soil evapotranspiration due to temperature. To reconstruct spatial PDSI, Van West calibrated historic June PDSI values against a principal components analysis of seven regional tree-ring chronologies (called SWOLD7, for Southwest Old Seven), using calibration periods that varied in length depending on available weather data, with 1915, 1922, 1924, 1928, and 1931 as starting years and 1970 as the ending year. The June PDSI values were calculated across 11 regional soil types using historical climate data from five regional weather stations (Van West 1994:Table 3.2). Van West's spatial model used soil productivity estimates from the Natural Resource Conservation Service

(Ramsey 2003) and generated independent productivity reconstructions for each of the 55 soil types and weather station combinations from AD 901 to 1970, extrapolating productivity measurements from historically dry-farmed soils to all major soil types in the region. Van West's major innovation was using a geographic information system (GIS) to generate the first spatial paleoproductivity reconstruction; she found that the CMV region could have supported thousands of people, even during the droughts in the twelfth and thirteenth centuries (Van West 1994:Figure 5.2).

Kohler and others (Kohler 2012) expanded on Van West's work as part of the VEP. Like Van West (1994), the VEP model calculated June PDSI over many regional soil types using historical climate data from four regional weather stations (corresponding to four elevation bands; Figure 3). These regional PDSI values were then correlated with a single tree-ring chronology (constructed from Douglas Fir on Mesa Verde [Dean and Robinson 1978:29–30]) and retrodicted to AD 600. Kohler and the VEP also account for high-frequency temperature change in their reconstruction by including two high-elevation bristlecone pine series—one from the San Francisco Peaks near Flagstaff, Arizona, and the other from Almagre Mountain in Colorado (Kohler 2012:88)[2]. Their final reconstruction (Kohler 2012:100) regresses historic maize yield on three series—reconstructed June PDSI, high-elevation temperature series, and year (to remove the technology trend)—to create paleoproduction estimates for AD 600 to 1300 (using 1931–1960 as the calibration period). Kohler (2012:Table 6.7) provides relevant correlation statistics. VEP researchers down-adjusted their estimates for hand-planting and high-elevation cold (Kohler 2012:100–108); these estimates may be further degraded dynamically by simulated farm families in the VEP agent-based simulation, depending on their density and continuity of field use. The hand planting adjustment was made to rule out portions of soils "that are too steep, rocky, boggy, or alkaline to be suitable even for hand planting" (Kohler 2012:103), using a Natural Resource Conservation Service (NRCS) determination of suitability. The cold-correction disallowed maize production on soils above 2395 masl and down-adjusted productivity linearly for elevations between 2150 and 2395 masl in cold years (years below the long term mean of the high-elevation temperature series [Kohler 2012:105–106]; see Note 10). Due to the inclusion of these production-suppression variables, the VEP model generated substantially lower production estimates than the Van West (1994) model, although the VEP also found that large populations could have been supported in the region, even during the worst droughts. A key point is that neither Van West's reconstructions nor the VEP reconstructions suggest that droughts in the twelfth and thirteenth centuries were particularly devastating for ancestral Pueblo communities; however, as noted above, the assessment of Benson et al. (2007:205) is that their impacts would have been dramatic. It is the purpose of this research to attempt to adjudicate between these two compelling yet contrasting visions of the Pueblo past.

Little effort has been made to directly model maize production outside of the CMV in the southwest US, presumably due to unavailability of local high-resolution climate proxies like tree-rings. Therrell et al. (2006) calibrate contemporary maize productivity between 1980–2001 to a single latewood

Douglas fir tree-ring chronology in central Mexico, which they use to reconstruct maize yield from 1474 to 2001. Their reconstruction is effective at capturing well-documented regional famines and droughts (Therrell et al. 2006:500). Annualized PDSI has been reconstructed across the contiguous United States extending back to AD 1000 using tree-ring-based correlation methods (Cook et al. 1999, 2010, 2014), but, to our knowledge, these retrodictions have yet to be transformed into maize paleoproductivity estimates[3] (but see Pool [2002, 2013], who generated his own PDSI reconstruction for estimating maize production in the Mimbres area).

In summary, the strategy of Burns (1983), Van West (1994), and the VEP (Kohler 2012) thus far has been to take historic, highly localized maize production data, correlate it with some derived measure of local growing conditions such as PDSI and temperature, correlate the growing conditions with long-term dendrochronologies, and, finally, retrodict maize production using these relationships.

Apart from relying on contemporary yield data that is of limited spatial extent and not readily available for other regions[4], this method has several shortcomings. First, it can only be applied in regions where maize farming occurred during the last century or so. Second, the use of linear models, even with multiple independent variables, will generate predictions that are not very sensitive to local conditions outside of the contemporary agricultural area. For instance, in the VEP study area, the contemporary maize data are assumed to come from the "bean fields": the area of present-day direct precipitation bean farming. Burns (1983) only had access to county-level data, but the method of Van West (1994) and the VEP (Kohler 2012) require the specific locations to which Burns' data apply. These bean fields have very little variation in topography or soil quality—both variables that factor heavily into the VEP model—and therefore are not a representative sample of growing conditions across the landscape. Contemporary Pueblo farmers take advantage of drainage basins and other natural runoff features that enhance soil moisture and can provide an important buffer during dry periods (Dominguez and Kolm 2005). Ancient and modern farmers also enhance the landscape in various ways, including runoff and subsurface moisture control features such as check dams. The Van West/VEP models are most appropriately considered reconstructions of direct-precipitation farming and not representative of more general rain-fed techniques that take advantage of natural and anthropogenic soil hydrologic characteristics. However, Brown (2016) used soil moisture proxy models to estimate soil hydrology around Goodman Point Pueblo (in the Van West/VEP study area) using methods that could be usefully extrapolated to the rest of the landscape in the future. Third, linear models, by definition, assume that maize production scales linearly with environmental variables, while, in reality, maize has specific environmental thresholds that must be met at several points during its growth cycle; maize production does not increase linearly above those thresholds (McMaster and Wilhelm 1997). For many variables, its response is curvilinear; high near optima and low on both sides (Jones et al. 1986; Van West 1994:99–101). Fourth, correlation models effectively reduce variance in predicted values; a series of chained, interdependent regressions reduces variance even further. This can lead to the entirely unrealistic expectation that, even in environments that are extremely unfavorable for agriculture, modest yields might still be achieved. Such is the case with the VEP productivity model. The regression relationship is not forced to have an intercept at zero (Kohler 2012:100), so there is always at least some potential productivity, except where the cold-correction is applied. In theory, the opposite effect could occur, given the right training data—the model could create expectations of negative yield. Correlation-based methods such as those described above should be adjusted to match the empirical yield distributions derived from empirical and, where available, experimental studies.

Experimental Studies

Research efforts have recently pivoted towards a focus on the phenology of ancestral maize landraces or statistical modeling of factors conditioning maize growth and development through experimental maize field trials and observational studies (Adams et al. 1999, 2006; Bellorado 2007, 2010; Bellorado and Anderson 2013; Dominguez and Kolm 2005; Muenchrath 1995; Muenchrath et al. 2017; Sundjordet 2017), local analysis of soil nutrient availability (Benson 2011a, 2011b; Homburg and Sandor 2011; Muenchrath et al. 2000), and other factors impacting maize growth (Adams 1979). Ancestral maize field trials have been thoroughly reviewed by Adams (2015), so we will only briefly summarize those efforts here. Other research not reviewed here has focused on the development and use of water and heat management technologies in maize cultivation, including cobble mulch gardens (Anschuetz 1995; Periman 1995), strategy diversification (Herhahn and Hill 1998), dry-farming in pumice soils (Gauthier et al. 2007), and the use of check dams (Doolittle 1985) and terraces (Sandor et al. 1990)[5].

Muenchrath (1995; Muenchrath et al. 2000, 2017), Adams (Adams et al. 1999, 2006), and others have steadily built a portfolio of experimentally derived growth data on ancestral maize landraces using maize field trials. In a series of field trials under variable precipitation, Muenchrath (1995) characterized the phenological and phenotypic responses of Tohono O'odham (Pima) maize. She found that kernel weight and the rate of grain-filling were little affected by precipitation amounts, especially when compared to other traits. More recently, Muenchrath (1995; Muenchrath et al. 2000, 2017), Werth (2007), and Adams et. al (2006) designed and executed a multi-year analysis of over 150 accessions of indigenous maize (the MAÍS project) near Farmington, NM. The plants were kept well-irrigated and fertilized (Adams et al. 2006:26–27), so the MAÍS trials primarily report growth and yield under optimal or temperature-limited conditions. Researchers collected data on the timing of planting and seedling emergence, flowering, and maturity, as well as weather data including accumulated heat (growing degree days [GDD]) and growing season length. Based on physical characteristics of the harvested maize, Adams et al. (2006) were able to partition the 150 accessions into four primary groups that corresponded well with known geographical and cultural distributions (Adams et al. 2006:43–44; see also Werth 2007).

In related research, Bellorado and others (Adams et al. 2008; Anderson 2008; Bellorado 2007, 2010; Bellorado and Anderson 2013) performed a small field trial in four garden plots in 2003 and 2004 using eight seed varieties (Adams et al.

2008:162). Maize was hand-pollinated, but otherwise left untreated (Adams et al. 2008:165). The relatively high-elevation setting of these field trials—between 6807 and 6896 feet (2075–2100 m) in elevation—and their position along the flanks of a broad basin generated good information on the importance of temperature for maize varieties. Bellorado (2007:185–193) reports that topographic variation substantially affected the length of the frost-free growing season, which likely impacted maize growth. Bellorado (2007) also tracked GDDs at the garden plots and could get reasonable yields of Hopi Red corn with as few as 1600 GDDs over the growing season (Bellorado 2007:205), a figure substantially lower than the heat requirements of contemporary varieties grown in the midwestern United States (~2400–3200 GDD) (Adams 2015; Muenchrath et al. 2017).

Several researchers have focused on the suitability of soils for various types of indigenous maize agriculture (Benson 2011a, 2011b; Homburg and Sandor 2011; Muenchrath et al. 2000, 2017). Muenchrath et al. (2000, 2017) and Homberg and Sandor (2011) have a long-standing research project on soil genesis and cropping systems in the Zuni region of central New Mexico. Recently, Benson (2011a, 2011b) published a large study of soil nutrients (particularly nitrogen and phosphorus) across the Colorado Plateau and into the Rio Grande region. He found that the central San Juan basin—the area around Chaco Canyon—has some of the least favorable soils for maize agriculture in the SWUS. Conversely, soils in Morefield Canyon on the Mesa Verde cuesta and on the Pajarito Plateau in northern New Mexico are among the most favorable places for maize agriculture (Benson 2011b:101–102). In these studies, Benson also used modern climate data to further establish temperature and precipitation growth requirements for indigenous maize under direct-precipitation farming (Bocinsky and Kohler 2014).

These initiatives—especially the MAÍS project (Adams et al. 2006)—have highlighted the great phenotypic and phenological variation among extant ancestral maize varieties in the SWUS and have provided important growth-data that may be used in more mechanistic reconstructions of maize yield, such as in cropping systems models (Pool 2002, 2013). Present-day traditional farmers utilize the diversity of their maize to minimize risk and fulfill ritual needs—a one-size-fits-all model of maize cannot guide archaeologists towards better understandings of these ritual and practical cultivation strategies in the past. Further, growth and yield data from field trials and soil analyses will help us to more accurately estimate potential maize yields in the past across a variety of landscapes. We now turn to the PFP, an experimental gardening research collaboration between the Hopi tribe and the Crow Canyon Archaeological Center that seeks to better understand ancestral Pueblo farming in the Mesa Verde region of southwestern Colorado.

The Pueblo Farming Project

The PFP has many goals that include conducting research, developing education programs, and pursuing Hopi interests in maize and maize farming as an essential element of their culture. We focus on one of the research goals here: using the PFP to evaluate and refine the VEP-model paleoproductivity estimates for ancestral Pueblo maize farming.

The PFP's beginnings can be traced to a 2004 Native American Graves and Repatriation Act (NAGPRA) consultation for Crow Canyon's Goodman Point Archaeological Project. Crow Canyon archaeologists met with the Hopi Cultural Preservation Office (CPO) to discuss the research design for this project. When we concluded the discussion of this research design, we asked the Hopi if there were research topics that interested them that were not covered in the proposal and they quickly responded that they wanted to know more about ancestral Pueblo farming and how it compared to the agricultural practices of Hopi and other Pueblo people today.

To follow through on this request, Crow Canyon developed the first of a series of grants to support a collaborative project on Pueblo farming. The initial grant funded a planning meeting in 2005 where we discussed the various types of research that could investigate ancestral Pueblo farming practices and link them to techniques used by modern Pueblo farmers. Participants at the meeting included traditional Pueblo farmers from Hopi, Jemez, Ohkay Owingeh, and Tesuque; Crow Canyon staff; and other anthropologists who specialize in the study of ancestral and modern Pueblo agriculture[6]. After two days of discussion, this group decided to implement an experimental gardening project that focused on rain-fed farming because this was the main type of farming practiced by the ancestral Pueblo in the Mesa Verde region. We used the term "rain-fed farming" to represent agricultural practices that use little to no large-scale landscape modification, but that readily take advantage of local landform and soil characteristics to enhance soil moisture (such as areas of higher runoff or greater snow accumulation) and often include small-scale anthropogenic modifications such as check dams. We considered direct-precipitation agriculture, a form of rain-fed farming. The group agreed that the Hopi should take the lead as the traditional farming experts, since they still practice rain-fed farming, whereas most other contemporary Pueblo tribes use more intensive flood-plain and canal irrigation techniques. Although the climate and landscape vary between the Hopi mesas and the central Mesa Verde region, ensuring adequate moisture for maize growth would have been a perennial concern in both regions (Benson et al. 2013; Bocinsky and Kohler 2014). Crow Canyon agreed to seek grant funding for the project that became known as the PFP[7].

The next step occurred in 2007, when Hopi farmers met to select locations for the gardens (Figure 4). We originally hoped to place these gardens at the Goodman Point Unit of Hovenweep National Monument to complement our ongoing research there, but we did not get permission for this and decided instead to locate the gardens on Crow Canyon's campus to integrate the PFP into the Center's education programs.

Pueblo farmers used traditional ecological knowledge to select the garden locations, focusing on the native plants that indicate good areas for farming[8]. Rabbitbrush (*Ericameria nauseosa*) and snakeweed (*Gutierrezia sarothrae*) are two plants they see as indicating prime areas, but dense stands of those plants were not present on Crow Canyon's campus. In the absence of such indicator species,

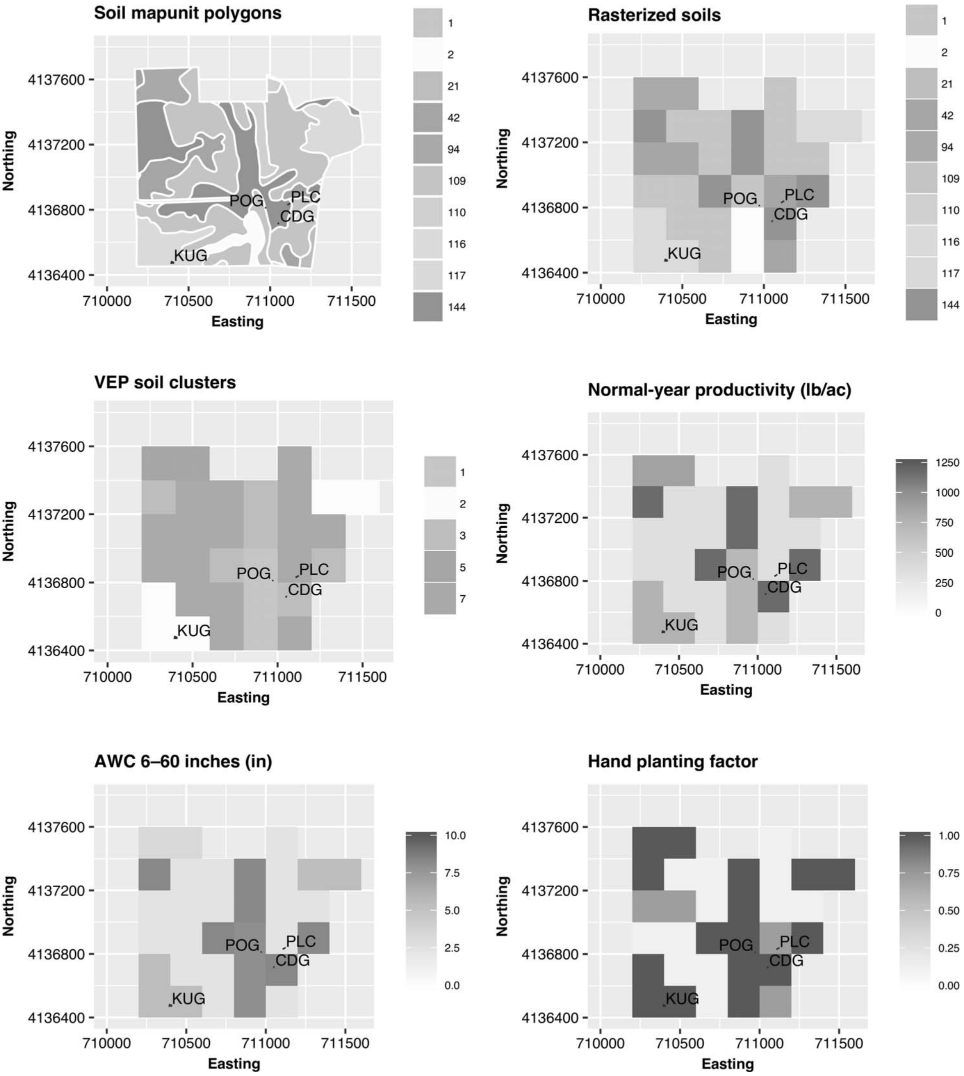

Figure 4. Map of NRCS soil complexes (mapunits) on the Crow Canyon campus, rasterized mapunits, and the NRCS soil cluster characteristics used in the VEP I maize paleoproductivity reconstruction. VEP researchers rasterized NRCS soil mapunits to a 200 × 200 m grid, and then used a clustering algorithm to create 14 soil clusters (see Note 11). Normal-year rangeland productivity is estimated by NRCS soil scientists from vegetation clippings (Ramsey 2003; Benson et al. 2013). Following Van West (1994), Available Water Content (AWC) is calculated within the soil column at depths from 6 to 60 inches (15.24–152.4 cm). The Hand Planting Factor is derived from a hand-planting suitability measure from the NRCS; see Kohler (2012:103). Eastings and northings are in Universal Transverse Mercator (UTM), Zone 12 units using the 1927 North American Datum (NAD27). All measurements are in the units used by the NRCS and VEP (usually English units). The locations of experimental gardens reported here are represented on each map. CDG: Check Dam Garden; KUG: Karen's Upper Garden; PLC: Pueblo Learning Center Garden; POG: Paul's Old Garden.

they selected two areas in small washes on the east side of Crow Canyon that are dominated by sagebrush (*Artemisia tridentata*) today. The farmers assessed soils for their texture and moisture-holding capacity and examined the details of specific settings including slope, aspect, and other factors. Although the Hopi farmers did not consider these two locations as ideal, they thought they would be adequate.

One location had sage (*Artemisia tridentata*) that was unusually tall; this area was located near the mouth of a small wash coming from the east slope of Crow Canyon. When this area was cleared, an ancient check dam was found and subsequently recorded (5MT19690). This was named the Check Dam Garden (CDG). The other plot was located higher up in a small drainage in an area where there was a thick patch of verdant grass; the Hopi farmers thought there might be a spring in this area, but subsequent work showed this was not the case. We call this plot the Pueblo Learning Center Garden (PLC) because it is on the way to one of Crow Canyon's outdoor classrooms.

In addition to these new plots, we continued planting a garden that Paul Ermigiotti had earlier developed for Crow Canyon's educational programs; this garden, Paul's Old Garden (POG), is in the bottom of Crow Canyon. In 2009, we added two additional garden areas. One, the Pithouse Garden (PHG), was placed on the west slope of Crow Canyon and adjacent to Crow Canyon's Pithouse Learning Center to incorporate the garden into the lessons that occur there. The other, Karen's Upper Garden (KUG), was a plot farmed by Karen Adams in the 1990s and located on the mesa just west of Crow Canyon. The KUG garden has produced relatively low yields, which surprised us because evidence suggests that the mesa tops covered in Mesa Verde loess-derived soils were the area most intensively farmed by ancestral Pueblo people based on the locations of early habitation sites (Adler 1990:239) and the largest Pueblo villages in the region (Glowacki and Ortman 2012:Table 14.1), and these loess-derived soils are most heavily utilized in contemporary dryland bean farming. To better evaluate the variation in these mesa-top settings, we created a new garden, the Mike Coffey Garden (MCG), in 2015 at Mike Coffey's farm near Dove Creek, Colorado. In this study, we only include data from four gardens: CDG, KUG, PLC, and POG. The PHG garden had anomalously low yields for several years and soil profiles showed that the area had been disturbed when the adjacent replica pithouse was constructed (the garden soils contained construction materials), so we abandoned this garden after the 2014 growing season. To date, we only have one season of data from the MCG, limiting its utility for calibrating paleoproduction models. Along with adding gardens in 2009, our recording methods changed slightly (see Materials and Methods), so data reported here only include the 2009 through 2015 growing seasons.

The PFP garden locations allow us to measure the effect of a variety of microenvironmental factors on agricultural potential. For example, the Crow Canyon gardens allow us to evaluate the effect of cold air that flows in drainages. The length of the frost-free period varies considerably despite relatively small differences in elevation and in the distance between the plots. The gardens are also located on soils with different characteristics and the effects of soil variability are the primary focus of this study (Table 1).

Table 1. NRCS soil classes, NRCS soil characteristics, and VEP I clustering. NRCS soil characteristics as reported in Figure 4.

Mapunit name	Mapunit key	VEP soil ID	VEP soil cluster	PFP Garden	AWC[a] 6–60 in. (in)[b]	Normal-year prod. (lb/ac)[c]	Hand planting factor
Wetherill loam, 3 to 6 percent slopes	57594	144	3	CDG	8.25	1167.1	1
Sharps-Cahona complex, 6 to 12 percent slopes	57563	116	2	KUG	5.38	754.5	1
Ackmen loam, 1 to 3 percent slopes	57543	1	1	POG	8.02	715.3	1
Gladel-Pulpit complex, 3 to 9 percent slopes	57646	42	7	PLC	2.39	337.1	0.72

[a] Available Water Capacity
[b] 15.24–152.4 cm
[c] kg/ha

Materials and Methods

Hopi participation in the PFP was coordinated by the Hopi CPO. The Hopi farmers who collaborate on the PFP include members of the Hopi CPO, members of the Hopi CPO Cultural Resource Advisory Task Team, and Hopi tribal members[9]. Hopi farmers provided the seed for the initial planting in 2008; we used seed from our harvests (primarily from the 2010 harvest) for planting in subsequent years. Hopi farmers also provided the expertise on how to plant, tend, and harvest the crops and they shared their insights into the important role that maize and maize farming plays in Hopi culture and how it is central to how Hopi people construct their identity.

In 2008, Hopi farmers brought 13 different varieties of their maize to Crow Canyon. The varieties selected for planting that year included blue (*sakwapqáö*), white (*ootsaqáö*), sweet (*tawaktsi*), greasy-head (*wiqwtö*), purple (*kokoma*), and Kachina (*katsinaqáö*) mixed-seed corn. Blue and white produced the largest yields in 2008, with greasy-head producing moderate harvests. Our planting in subsequent years has focused on blue and white varieties (Table 2).

Planting was done with planting sticks and Hopi expertise included instruction on how deep to plant, the spacing between clumps (as opposed to planting in rows; see below), how many seeds to plant in each hole, and how to dig and refill the hole. Instruction on tending the gardens included how and when thinning should occur, how to control for pests, and how to control for weeds. Hopi agriculture emphasizes the management of the limited amount of soil moisture available from direct precipitation and runoff (Dominguez and Kolm 2005). These techniques have also been documented and discussed by others who worked extensively with Hopi farmers during research on their agricultural practices (e.g., Bellorado 2007; Dominguez and Kolm 2005) and the information provided during the PFP rarely contradicted earlier accounts.

Table 2. Details of PFP experiments by garden, and average PFP experimental and VEP estimated maize yields.

Garden	Season	Variety	Clumps	Spacing (m)	PFP experimental yield (kg/ha)	VEP estimated yield (kg/ha)
CDG	2009	Hopi Blue	35	1.6	133.1	612.2
CDG	2010	Hopi White	26	1.4	1372	687.4
CDG	2011	Hopi White	26	1.75	139.8	618
CDG	2012	Hopi White	21	1.5	0	535.8
CDG	2013	Hopi White	27	1.75	246.9	552.9
CDG	2014	Hopi White	25	1.75	31.4	553.7
CDG	2015	Hopi White	47	1.75	355.2	689.6
KUG	2009	Hopi Sweet	62	1.7	0	391.7
KUG	2010	Hopi Blue	77	1.6	186.1	453.3
KUG	2011	Hopi Blue	36	2	36.7	401.1
KUG	2012	Hopi Blue	32	1.85	2.5	356.8
KUG	2013	Hopi Blue	31	2	34.6	367.2
KUG	2014	Hopi Blue	29	2	1.7	354.2
KUG	2015	Hopi Blue	36	2.25	192.6	451.7
PLC	2009	Kokoma (purple)	32	1.8	0.1	124.4
PLC	2010	Greasy-head & Hopi Blue	38	1.2	296.1	138.5
PLC	2011	Hopi Blue	39	1.5	1.4	140.8
PLC	2012	Hopi Blue	23	1.75	0	116
PLC	2013	Hopi Blue	34	1.75	5.7	113.9
PLC	2014	Hopi Blue	28	1.75	0	117
PLC	2015	Hopi Blue	30	1.5	305.2	153.8
POG	2009	Greasy-head	28	1.5	193.2	375.2
POG	2010	Greasy-head	30	1.5	359.9	421.9
POG	2011	Hopi White	26	1.5	253	378.7
POG	2012	Hopi White	20	1.5	0	328.3
POG	2013	Hopi White	25	1.75	1.2	339.2
POG	2014	Hopi White	20	1.5	0	339.1
POG	2015	Hopi White	20	1.75	673.8	422.8

The gardens were fenced to help mitigate pest damage. The PLC, CDG, and KUG gardens were fenced with approximate 2 m-high wire fencing on wooden and metal posts; the POG garden fence was only about a meter high and was constructed with willow branches. Consequently, the POG garden may have been subject to more pest damage than the other gardens.

One of the most important techniques is deep planting to ensure that the seed is placed in soil with sufficient moisture for germination, although in the driest years moisture is limited at any depth. The planting hole can be as much as 30 cm (~12 inches) deep. On the Hopi Mesas, planting is often deeper (as deep as 40–45 cm; Bousselot et al. 2017; Dominguez and Kolm 2005:755–756); the Hopi farmers described digging a hole just until the soil at the bottom of the hole feels or appears moist. When soil removed from the hole is replaced, care is taken to put the moist sediments from the bottom of the hole on top of the seeds and driest soil on top where it serves as a dust mulch. Between eight and twelve seeds are placed in a single planting hole, although the Hopi farmers never make an exact count. There are advantages to planting many seeds in a single clump; this can help to ensure adequate germination and, when the plants are small, those on the outside of the clump protect those on the inside from the spring winds. The spacing between the plantings is three paces or about two meters apart (Beaglehole 1937:40; Bellorado 2007:95–96; Dominguez and Kolm 2005)—this wide spacing ensures that each clump does not have to compete with its neighbor for soil moisture. In the PFP gardens, however, spacing was often far tighter between clumps (Table 2). It is impossible to know at this time whether this is due to the artificially-small enclosures around the PFP gardens or a response to the generally higher soil moisture in the Mesa Verde region as compared to the Hopi mesas.

The clumps were thinned when they were about knee-high or when the leaves first become long enough to bend over and touch the ground, which occurred in early-to-mid July in the Crow Canyon gardens. The thinning removes any plants that have been damaged by wind, insects, or plants that are lanky and spindly; thinning reduces the number of plants in each clump to about six. Thinned plant material was left on the surface and acted as a vegetal mulch.

Sundjordet (2017) points out that drought not only limits the growth of maize, but also all other vegetation and this means maize plants are targeted by pests to a greater degree in dry years. When insects became a problem in our gardens, the Hopi recommended soaking dog dung in water until the dung dissolved and then applying this solution with a piece of rabbitbrush that was dipped into the mixture and shaken onto the plants. We did not follow this recommendation—animal pest control during the growing season was restricted to building and maintaining fenced-in enclosures around each garden.

The Hopi wait to harvest until the ears on the maize plants have dried considerably; the sign that they are ready to harvest is when the ears fall from their upright position and drop so the top of the ear points toward the ground. In these experiments, the Hopi farmers were present for harvest and, consequently, harvesting was scheduled for mid-October; we therefore could not time harvest as precisely as Hopi farmers would for their own gardens, but harvest was often after the first killing frost when grain-filling had ceased.

Under the direction of Paul Ermigiotti, stages of vegetative and reproductive growth were recorded in each garden every week from germination to the first killing frost. This included counting the number of plants in each clump; measuring the height of the tallest plants in each clump; recording the appearance of tasseling, silking, and ear formation; and documenting insect damage and other signs of stress. At harvest, we recorded the number of ears from each clump. After harvest, the dried ears from each clump were recorded and ear and kernel weights were recorded. We did not record wet weights of ears during the 2009–2015 seasons, but did in 2016 and will do so going forward. Based on the percentage of kernels present, ears were classified as full, partial, sparse, and immature. In a handful of instances, an ear was withheld from processing to serve as an example in Crow Canyon's educational programs; in those cases, we estimated kernel weights using the average ratio of kernel to ear weight ratio from all other ears multiplied by the measured ear weight[10].

The kernel weight from each clump for each garden was used to extrapolate a distribution of yields for each garden in each year[10]. We did so in two ways. In the first method, given the variability in spacing by garden and year (Table 2), we calculated the yield for any given clump by dividing its kernel weight by the square of its garden's clump spacing in that year and converted to kilograms per hectare. Spacing within each garden in each year was reasonably consistent. In the second method, we attempted to standardize across all of the gardens by using a 2 m clump spacing and calculated the yield for any given clump by dividing its kernel weight by 4 m^2 (2 m x 2 m). The standardized measurements are used in the analyses presented here to make yield estimates among the gardens comparable between themselves and to the VEP productivity estimates[11].

It is important to note that not only were our choice of garden locations not necessarily ideal, but our farming effort was minimal. Other than the weekly recording, ongoing work in the gardens was limited and likely far less than the labor inputs by ancestral Pueblo farmers. For example, we only occasionally replanted plots if the first planting resulted in poor germination or if small plants were damaged or killed by pests[10]. We did not pot-irrigate newly planted fields during severe drought years to achieve germination and we were only able to weed occasionally. We only visited the gardens once a week and did not monitor gardens every day for pests. We simply did not have time to accomplish a variety of farming practices described by our Hopi colleagues and in early accounts of Pueblo agriculture (e.g., Beaglehole 1937; Bradfield 1971; Cushing 1974; Forde 1931; Stephen 1936; Sundjordet 2017; Underhill 1946; Whiting 1936). Perhaps even more important, our efforts during the time between planting and harvesting were not informed by the expertise that ancestral Pueblo farmers possessed. The small size of the gardens and the proximity of the surrounding vegetation might also reduce yields compared to those obtained from a larger field. These limitations probably produced lower yields than those obtained by ancestral Pueblo farmers and this should be kept in mind when evaluating the PFP yields.

We estimated VEP-style yields for 2009 to 2015 by adapting the VEP paleoproductivity method (Kohler 2012) not to rely on tree-ring chronologies (which generally do not extend into this millennium). We calculated VEP estimates for all soils on the Crow Canyon Archaeological Center campus (Figure 4; Table 3) and extracted estimates of net primary productivity, average potential bean yield, the available water capacity from 6 to 60 inches (15.24–152.4 cm) below ground surface, and a hand-planting reduction (Figure 4; Table 1) from the NRCS soil survey for Montezuma County (Ramsey 2003), following Kohler (2012). We calculated monthly PDSI estimates using the *scpdsi* command-line program available from the University of Nebraska–Lincoln (Wells et al. 2004), modified to run from *R*, and historical daily weather data from the Cortez, Colorado weather station of the Global Historical Climatology Network (station ID USC00051886). The reconstructions relied on calibrations used by the VEP, including the relationship between historical yield (as

Table 3. Mean and variance of PFP experimental and VEP I estimated maize yields (kg/ha). "Modern" estimates are over 2009–2015; "ancient" estimates are for AD 600–1300, and are directly from the VEP (Kohler 2012). See the supplementary information.

Garden	PFP experimental yield: mean	VEP estimated yield: mean, modern	VEP estimated yield: mean, ancient	PFP experimental yield: SD	VEP estimated yield: SD, modern	VEP estimated yield: SD, ancient
CDG	325.5	607.1	568.8	477.2	63.6	95.3
KUG	64.9	396.6	160.4	86.4	41.9	24.6
PLC	86.9	129.2	68.3	146.1	15.3	11.4
POG	211.6	372.2	160.4	248.8	39.1	24.6

calculated by Burns [1983]) and regional average June PDSI (as calculated by Van West [1994]). See Note 11 for information about accessing all input data and for a script in *R* that calculates the VEP estimates. The VEP method is thoroughly documented by Kohler (2012).

Results

Data on garden locations, planting, and measurements for all harvested ears are provided as supplemental information via Zenodo, as is a script in the *R* statistical language for reproducing all tables and figures presented here[11]. We rely heavily on the *FedData* (version 2.4.0; Bocinsky 2017), *dplyr* (version 0.5.0; Wickam and Francois 2016), *sp* (Pebesma and Bivand 2005), and *raster* (Hijmans 2016) packages for *R*; other useful packages are referred to in the *R* code.

Experimental maize yields were highly variable from year-to-year, garden-to-garden, and even between clumps in any given garden (Figure 5; Tables 2 and 3). For instance, there was a difference of almost 1750 kg/ha in yields extrapolated from the lowest and highest producing clumps at CDG in 2010. Figure 5 shows the experimental yields for each garden in each year. The box plots represent the yields extrapolated from each clump; the asterisk in each box plot is the mean yield across clumps. Superimposed on the garden yields are the yields for each garden as estimated using the VEP I method (the solid lines in Figure 5). The average experimental and estimated yields for each garden are highly correlated (Table 4), though the VEP estimates show far less variability from season to season than the experimental gardens. In bad years (2009, 2011–2014), experimental yields were far lower than estimated by the VEP, both for the "modern" (2009–2015) and in the "ancient" (AD 600–1300) VEP reconstruction (Table 3); in good years (2010, 2015), experimental and estimated yields were more aligned and estimates were exceeded by a large amount at the CDG in 2010. Additionally, in bad years, the experimental yield distributions are heavily skewed towards zero—there are many clumps that did not produce any yield[10].

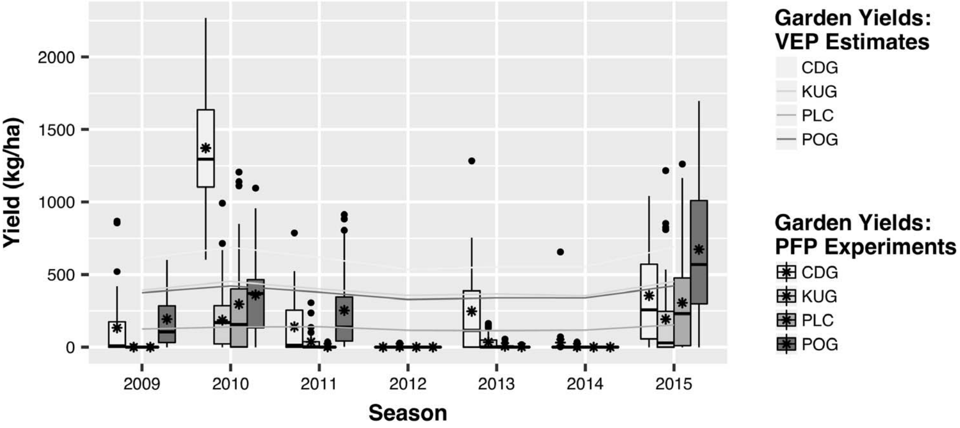

Figure 5. Experimental (PFP) and estimated (VEP) garden yields. Box plots indicate the distribution of experimental yields as extrapolated from individual clumps; the lower and upper bounds of each box are at the first and third quartiles; the second quartile (50th percentile) is noted by the line within each box; whiskers extend no further than 1.5 times the interquartile range; data beyond the end of the whiskers are the outlying points. Asterisks mark the distribution means. CDG: Check Dam Garden; KUG: Karen's Upper Garden; PLC: Pueblo Learning Center Garden; POG: Paul's Old Garden.

Discussion and Conclusion

What information can the PFP and other experimental studies give us about production estimates for the ancestral Pueblo past? As stated above, the VEP estimated yields and average PFP experimental yields are highly correlated and yet the estimated yields are far less variable than the experimental yields. This suggests that a simple scaling and transformation of the VEP estimates (e.g., mean-variance matching; Bocinsky and Kohler 2014; Towner and Salzer 2013)—and thresholding at zero production—might adequately re-calibrate the VEP estimates. More accurately, our goal should be for the VEP estimates to roughly match the empirical probability distribution of the experimental yields. The appropriate probability distribution to model agricultural yields is a matter of considerable debate in agro-economics and a discussion of it is well beyond the scope of this paper (but see Day 1965; Just and Weninger 1999; Nelson and Preckel 1989). However, it is clear that correlation-based estimates of ancient production are, unsurprisingly, not nearly as variable as we might expect people to have experienced in the past.

Table 4. Correlation between PFP experimental and VEP I estimated maize yields.

Garden	Correlation (r)	P-value	Lower CI	Upper CI
CDG	0.7	0.083	−0.12	0.95
KUG	0.93	0.003	0.58	0.99
PLC	0.76	0.047	0.02	0.96
POG	0.93	0.003	0.58	0.99

But perhaps even more important is that the results of the PFP serve as a cautionary tale for those who hope to model potential agricultural yields in the past. Agricultural production, like any bio-ecological process, is dependent on very many factors and, in a cultivar like maize, human agency plays a starring role. Where and when to plant, and what variety, are only a few of the crucial decisions; the farmers in this study made several expert and culturally-guided decisions, such as how deep to plant and how many seeds to place in each clump, and they provided guidance on when and how much to thin the clumps. Perhaps more important are the quotidian acts of the farmer not addressed in this study—weeding, irrigating, and protecting one's crops from pests—as our Hopi colleagues and those interviewed in similar studies attest (e.g., Sundjordet 2017).

How can agricultural productivity models incorporate these important human elements of ancient (and contemporary) agriculture? We might take a page from contemporary precision agriculture and use decision support systems such as cropping systems models to simulate production under culturally and archaeologically-informed cultivation techniques (see, for example, Bocinsky 2014; Pool 2002, 2013). To successfully do so, however, requires further research in three areas. The first is ethno-agricultural research in the vein of Whiting (1936) that faithfully records traditional agricultural techniques, such as studies by Dominguez and Kolm (2005), Sundjordet (2017), and the PFP. The second is formal agronomic field trials to collect essential phenological data about different cultivar varieties, such as the MAÍS project (Adams et al. 2006). Finally, employing tools from precision agriculture will require archaeologists to engage more deeply with the paleoclimate community—decision support systems often require daily-level weather data, which for the past must be simulated using sophisticated computer models. Projects such as Synthesizing Knowledge of Past Environments[12] and the National Oceanic and Atmospheric Administration paleoclimatology database[13] are bringing state-of-the-art data to researchers, but more work needs to be done to bring these data to spatio-temporal scales relevant to human experience (d'Alpoim Guedes et al. 2016).

Culturally-informed experimental farming studies such as the PFP are essential for understanding the challenges and adaptations of ancestral farming communities. The PFP experiments have demonstrated that Hopi varieties of maize—though currently grown in an environment much different from southwestern Colorado—are able to flourish in the upland Southwest when planted in suitable locations using traditional Hopi cultivation methods. Future PFP research will focus on how quickly Hopi landraces can adapt to local conditions—an attribute that would have been highly advantageous for a culture with a history of migration across the highly variable landscape of the US Southwest.

Notes

[1] Burns (1983) had to estimate data from 1944–1947, for which no yields were published.

[2] Kohler and the VEP (Kohler 2012) also used the first principal component of these two series to construct a joint series (the "Prin1" series).

[3] Maize paleoproductivity estimates could easily be generated from the NADA reconstructions by using transfer functions derived by Van West (1994).

[4] Had it not been for Burns aggregating historic production data from Montezuma County, Colorado, neither Van West's nor the VEP reconstruction would likely exist.

[5] While these methods were widely-used in other areas of the Southwest, they were less-used in the central Mesa Verde region.

[6] The Pueblo farmers who attended this meeting included Herman Agoyo, Ohkay Owingeh; Bradley Balenquah, Hopi; Louie Hena, Tesuque; Frank Hohnahnie, Hopi; Wilton Kooyahoema, Hopi; Leigh Kuwanwisiwma, Hopi; Marvin Lalo, Hopi; Tom Lucero, Jemez; Harold Polyingyumptewa, Hopi; John Romero, Jemez; and Kevin Shendo, Jemez. Consultant anthropologists included Kurt Anschuetz, Steven Dominguez (Sundjordet), and Richard Ford.

[7] Grant support for planning and implementing the PFP includes funding from The Christensen Fund, the National Geographic Society's Genographic Legacy Fund, the Colorado State Historic Fund, and the National Science Foundation.

[8] Garden locations were selected by Hopi farmers Leigh Kuwanwisiwma, Lee Wayne Lomayestewa, Owen Numkena, Raleigh Puhuyaoma, and Morgan Saufkie, and Jemez farmer Tom Lucero.

[9] Hopi farmers who planted and harvested PFP gardens between 2008 and 2016 include Donald Dawahongnewa, Akema Honyumptewa, Stewart Koyiymuptewa, Leigh Kuwanwisiwma, Lee Wayne Lomayestewa, Gary Nichlas, Lance Nichlas, Owen Numkena, Harold Polingyumptewa Raleigh Puhuyaoma, Morgan Saufkie, and Ronald Wadsworth. Herman Agoyo from Ohkay Owhingeh and Tom Lucero from Jemez also participated.

[10] PFP growth and production data will be analyzed in a forthcoming publication, and are currently available at https://github.com/crowcanyon/pfp_shiny; a website that presents these data graphically is in draft form at http://shiny.crowcanyon.org/pfp/.

[11] A research compendium including data used in this study and all code for performing these analyses can be found at: https://doi.org/10.5281/zenodo.398863.

[12] https://www.openskope.org/.

[13] https://www.ncdc.noaa.gov/data-access/paleoclimatology-data.

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