Title

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Population and Environmental Correlates of Maize Yields in Mesoamerica: a Test of Boserup's Hypothesis in the *Milpa*

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Abstract Using a sample of 40 sources reporting *milpa* and *mucuna*-intercropped maize yields in Mesoamerica, we test Boserup's (1965) prediction that fallow is reduced as a result of growing population density. We further examine direct and indirect effects of population density on yield. We find only mixed support for Boserupian intensification. Fallow periods decrease slightly with increasing population density in this sample, but the relationship is weak. Controlling for other covariates, fallow-unadjusted maize yields first rise then fall with population density. Fallow-adjusted maize yields peak at 390 kg/ha/yr for low population densities (8 persons / km^2) and decline to around 280 kg/ha/yr for the highest population densities observed in our dataset. Fallow practices do not appear to mediate the relationship between population density and yield. The multi-level modeling methods we adopt allow for data clustering, accurate estimates of group-level variation, and they generate conditional predictions, all features essential to the comparative study of prehistoric and contemporary agricultural yields.

Keywords Boserup · Agricultural intensification · *Milpa* · Maize · Agro-ecology · Multi-level analysis · Mesoamerican and Maya subsistence

Introduction

In her 1965 book, *The Conditions of Agricultural Growth*, Esther Boserup proposes a synthetic, general account of agricultural development. Taking population growth and consequently population "pressure" as an exogenous, driving variable, Boserup argued that agricultural systems typically intensified from long-fallow, extensive systems to progressively shorter fallows, and then to multi-cropped, intensive forms of agrarian production. Returns to labor diminish as human effort, time and resource-intensive technologies like mulching, manuring and irrigation replace the regenerative effects of long fallows. Yield per unit area of available land grows as land is more productive and more continuously cultivated, elevating its capacity to support human population. Because humans generally avoid unnecessary exertion, Boserup noted that extensive forms of production prevail when land is abundant relative to population requirements; intensive forms will prevail when it is scarce. Thus, while intensification predominates, agricultural development might go in either direction depending on the availability of land and the distribution and density of populations (Netting 1993).

Boserup's theory is taken to be a decisive alternative to the Malthusian claims that food shortages inevitably cap

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population density at a level set by technology. The theory has proven attractive not only to agricultural historians and development economists but also to prehistorians, geographers and anthropologists eager to understand mechanisms involved in the development of early human societies dependent on agriculture (see "Discussion: Boserup in the Milpa" for citations).

We perform a comparative, multilevel-analysis of primary data on fallow periods and yields of *milpa* (shifting cultivation) maize agriculture, a form of production widely practiced in Mesoamerica and adjacent regions. We present three related models involving population density as a focal predictor along with environmental and geographical covariates. In the first model we examine the frequency of planting relative to fallow; and in subsequent models we examine two different forms of maize yields. We assess whether or not small-scale farmers intensify agricultural production by shortening the fallow period. Our study recognizes that intensified production might also be a result of enhanced yield per unit of land (Netting 1993: 262), independently of fallow.

Coincident with our test of the Boserup hypothesis, we evaluate the importance of population density relative to other potential predictors of yield (e.g., elevation, rainfall and soils) and suggest how the resulting analysis may be used to address issues ranging from the ability of *milpa* production to support the populations presumed to be associated with Classic Period Maya societies (Ford and Clarke n.d.) to the contemporary outlook for this form of agro-ecological production.

The Sample

Milpa Maize Data Sources

Through library searches and personal correspondence with scholars working on questions of agricultural production in Mesoamerica and adjacent regions we identified 40 primary sources reporting original data on maize yields between 1931 and 2011. We focused on traditional slash-and-burn *milpa* practices as well as *mucuna*, a modification in which maize is intercropped with a cover crop, the velvet bean (Triomphe and Sain 2004). Our sample produced a total of 297 records from 92 communities. Figure 1 shows the geographical distribution of the sample locations. Table S1 (Supplemental Materials) provides a full description of the dataset; Table S2 describes the list of variables we have derived from these primary references or from supplementary sources where that proved necessary. The Supplemental Materials section titled "Sample Preparation" describes our methods.

Descriptive Results

Two Measures of Production

Two measures of production are important to the Boserup hypothesis. *Unadjusted Yield* is edible or useful offtake from one planting measured in weight, bulk, nutrient or other value per unit area. This is the variable found in the primary literature in most cases. *Adjusted yield* takes into account the frequency with which an area of soil will produce a particular amount of food or materials. It corrects for agricultural intensification based on fallow length and intra-annual multi-cropping:

$$\begin{aligned} &\mathit{Adjusted\ yield} \\ &\quad = \mathit{total\ yield}{*}\mathit{years\ cropped} \Big/ (\mathit{years\ cropped} + \mathit{years\ fallow}) \end{aligned}$$

where *total yield* corresponds to the sum of the first and second harvest season of maize produced during the agricultural year. A *total yield* of 1000 kg/ha for 1 year of production in an agro-ecological system requiring 9 years of fallow implies an *adjusted yield* over the full agricultural cycle of 100 kg/ha/yr. The system that produces 1500 kg/ha for 2 years followed by a fallow of 3 years is capable of an *adjusted yield* of 600 kg/ha/yr. This six-fold difference is of significance to the farmer and also to the political economy of the region. It also is important to Boserup's theory, because intensification can occur through squeezing more yield/unit area from each planting, or by planting each area more frequently relative to fallow, or by a combination of the two.

Unadjusted Yields

Figure 2 shows the range of reported *unadjusted yields* (kg/ha) by source, arrayed from low to high by medians for the full dataset. The median for all *milpa* cases is 1133 kg/ha, while the median for all *mucuna* cases is 3121 kg/ha. The wide range of *unadjusted yields* observed from some sources reflects in part differences between first and second season maize harvests. Cases for which *milpa unadjusted yields* rest close to *mucuna unadjusted yields* (those nearer the top of Fig. 2) were observed among the Lacandones in Chiapas, Mexico (Diemont, *et al.* 2006; Nations and Nigh 1980), the Kekchi in Uaxactun (Urrutia 1967), the Mestizos in Veracruz (Coe and Diehl 1980) and other groups in Guatemala (Stadelman 1940). Of these, the Lacandones are known for intensively managing their environment (Nigh and Diemont 2013). Table S3 provides median and 1st and 3rd quartile values for the *unadjusted yields* presented in Fig. 2.

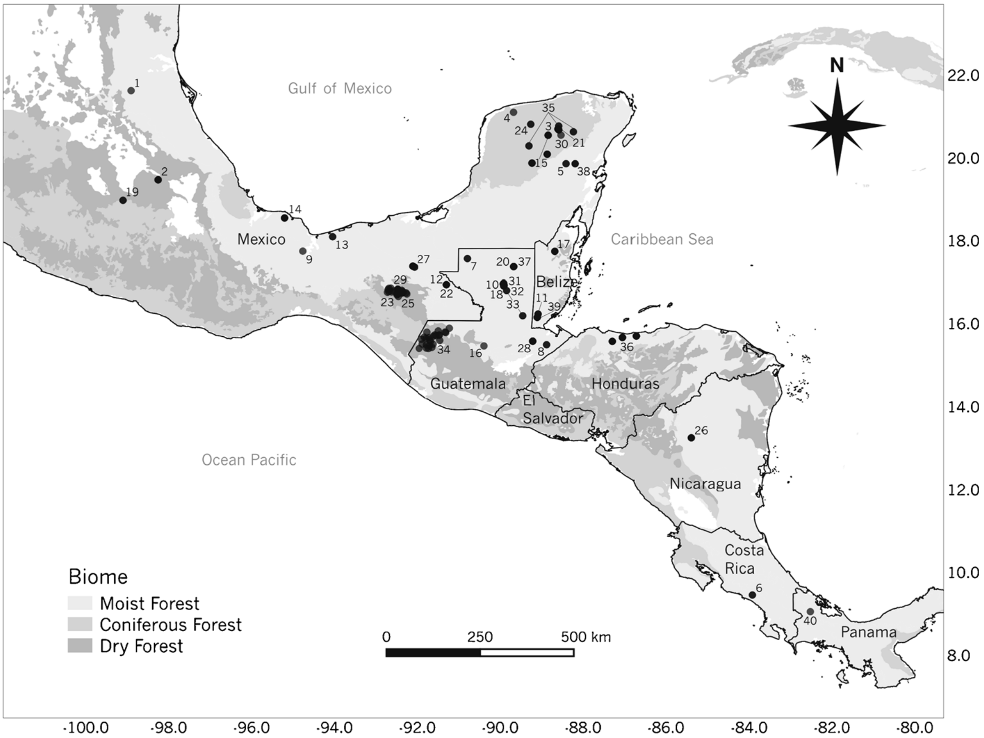


Fig. 1 Geographical distribution of data sources by country and biome. The 40 sample locations are: (*1*) (Alcorn 1989). (*2*) (Altieri and Trujillo 1987). (*3*) (Arias Reyes 1980). (*4*) (Askinasy 1935 & Shuman 1974, as cited in Ringle 1985). (*5*) (Baraona and Montalvo 1981). (*6*) (Barlett 1977). (*7*) (Carr 2008). (*8*) (Carter 1969). (*9*) (Coe and Diehl 1980). (*10*) (Cowgill 1961). (*11*) (Culleton 2012). (*12*) (Diemont, *et al.* 2006). (*13*) (Drucker and Heizer 1960). (*14*) (Eilittä, *et al.* 2004). (*15*) (Graefe 2003). (*16*) (Higbee 1947). (*17*) (Lambert and Arnason 1986). (*18*) (Lara Ponce 2010). (*19*) (Lewis 1951). (*20*) (Litow 2000). (*21*) (Morley and Brainerd 1956). (*22*) (Nations and Nigh 1980). (*23*) (Nigh 1976). (*24*) (Pascual and Barbier 2006). (*25*) (Perales, *et al.* 2005). (*26*) (Philipp and Gamboa 2003). (*27*) (Pool Novelo, *et al.* 1998). (*28*) (Popenoe 1967). (*29*) (Preciado Llamas 1976). (*30*) (Redfield and Villa Rojas 1962). (*31*) (Reina 1967). (*32*) (Sanders & Rice 1993, as cited in Griffin 2012). (*33*) (Schwartz 1990). (*34*) (Stadelman 1940). (*35*) (Steggerda 1941). (*36*) (Triomphe and Sain 2004). (*37*) (Urrutia 1967). (*38*) (Villa Rojas 1945). (*39*) (Wilk 1997); and, (*40*) (Young 1971)

Explanatory Variables

Figure 3 shows relationships between pairs of continuous variables using scatter plots overlaid with cubic splines. The top two rows of the matrix guide construction of our predictive models for *effective fallow* and *unadjusted yield. Effective fallow* is a derived variable reflecting the degree to which a particular piece of earth is in continuous production, thus a measure of Boserupian intensification:

$$Effective\ fallow = (years\ cropped + years\ fallow) \Big/ (years\ cropped * crops\ per\ year).$$

If fallow is eliminated, this reduces to 1 / *crop(s) per year.*

Unadjusted yield is the vertical axis in all of the plots of the first row. We note potential non-linear relationships with some covariates, as well as structural features of the dataset: vertical stripes in the scatter for *population density, elevation* and *rainfall* (which might otherwise be expected to vary continuously within their ranges) indicate clusters of observations reported by the same primary source. For *effective fallow,* a few clusters having both large *unadjusted yield* and large *effective fallow* appear to bend the curve into a concave shape, but overall the scatter shows a flat or descending trend. We observe potentially parabolic relationships for *population density* and *elevation*, suggesting that both linear and squared terms for these predictors should be included in regression models. *Rainfall* shows two peaks: a lower intermediate optimum precipitation we know to be associated with *milpa* fields, which are more common in drier climates, and a higher optimum for *mucuna*, more common in wetter climates. This indicates that linear and squared terms for *rainfall*, along with *strategy* interactions, should be investigated.

Effective fallow is the vertical axis of the plots in the second row. The relative coarseness of this variable – with many cases sharing characteristic fallow cycles – makes visual interpretation challenging. There is a suggestion that *effective fallow* declines with increasing *population density* and *calendar year,* as well as evidence for non-linearity with respect to *elevation* and *rainfall*. Because of the intrinsic relationship between *year in cycle* and *years cropped,* the latter appearing in the formula for *effective fallow*, we do not use *year in cycle* in a predictive model for *effective fallow.*

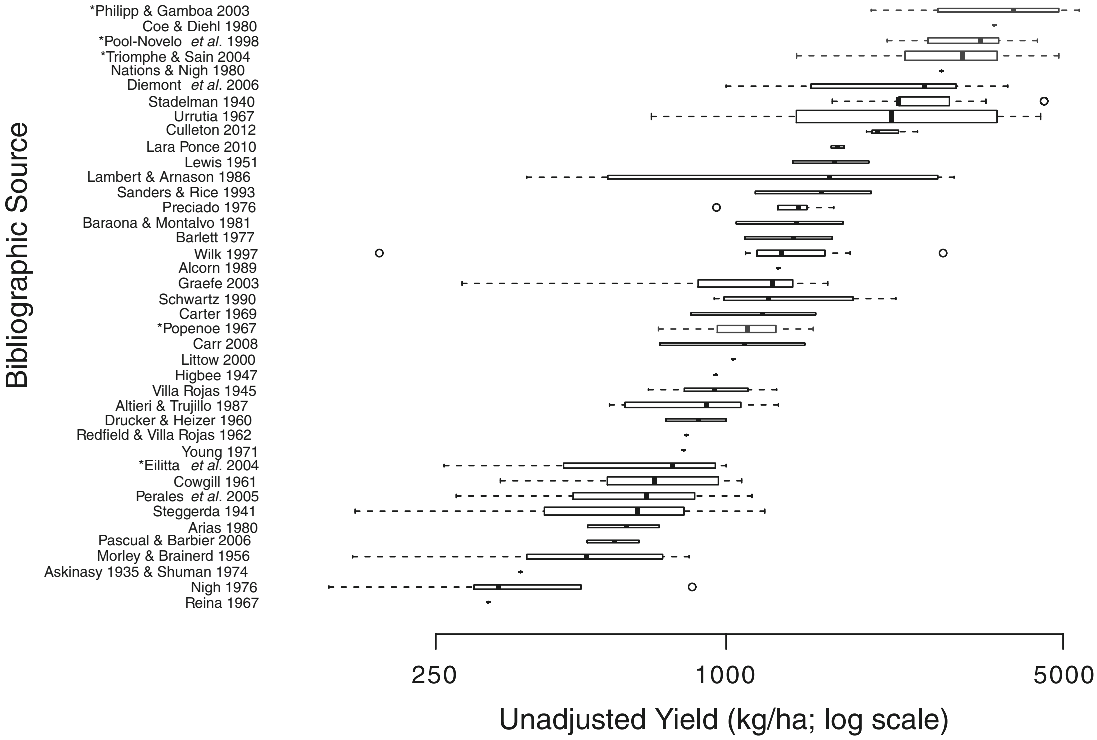


Fig. 2 Distribution of maize yield data by source, arranged low to high by median value. Each source is represented by a variable width, whiskered box plot, with width scaled by the square root of the number of observations and outliers segregated by using standard conventions (R Core Team 2013). Sources without an asterisk correspond to *milpa*-only measurements; those with an asterisk to a mix of *milpa* and *mucuna*, except for Philipp and Gamboa (2003) who only report *mucuna*. Seven of the cases represented include both 1st and 2nd season yields. Reading top down they are: (Lambert and Arnason 1986) (Carter 1969) (Popenoe 1967) (Carr 2008) (Drucker and Heizer 1960) (Eilittä, *et al.* 2004) (Cowgill 1961). Two cases represent 2nd season yields only: (Philipp and Gamboa 2003; Triomphe and Sain 2004). The remaining cases represent yields for the 1st season crop. Some data within Graefe (2003), Schwartz (1990), and Higbee (1947) were excluded from the sample because they lack information on the fallow period. Not included here are eight more sources reporting maize yields but also lacking information on the crop to fallow ratio. These are: (Eastmond and Faust 2006; Fernandez Ortiz and Wasserstrom 1977; Immink and Alarcon 1993; Isakson 2007; Sanders 1973), (Puleston 1968 and Wiseman 1978, as reported in Griffin 2012: 59–60), (Rickeston & Rickeston 1937, as reported in Ringle 1985: 374) and (Vogeler 1974)

Box plots (Fig. 4) allow us to examine similar relationships between *effective fallow* and *unadjusted yield* and categorical covariates. For *unadjusted yield* (right panel), the *strategy milpa* shows a much wider range than *mucuna*. Some of the difference in variance may be attributed to different sample sizes (*milpa* $n=254$; *mucuna* $n=43$) but it is clear that on average *mucuna* is the more productive *strategy*. The highest median *unadjusted yields* are associated with the biome *moist forest*, followed in order by *coniferous* and *dry forest*. *Effective fallow* (left panel) is typically larger for *strategy milpa*. *Mucuna* is associated with few fallow years relative to crop cycles, with a median halfway between a multicropping and a grass fallow agricultural intensity level (see Turner II 1976: 80). The *dry forest* biome has the largest median *effective fallow*, followed in order by *coniferous* and *moist forest*. There is wide overlap across the three biome types for *unadjusted yield* and *effective fallow*.

Box plots showing *unadjusted yield* in relation to *soil qualities'* constraint levels (Fig. 5; right panel) identify soil *toxicity*, *excess salts* and poorer *rooting conditions* as factors reducing yields. Trends in the effects of soil quality on *effective fallow* (left panel) are not easily discerned.

Analytical Approach

Three Models for Boserup's Hypothesis

Boserup's theory suggests three predictive models (Fig. 6). Boserup's fundamental claim – that farmers reduce fallow periods in response to increases in population density, hence population pressure – is captured by Model M. Although *population density* is the focal predictor in Model M, we control for other variables such as *elevation* and *rainfall*, both of which determine background conditions relevant to farmer decision-making and yield. These variables, discussed below, are collectively the *other covariates* in Models M, Y and A. They are especially important because geographic and ecological controls allow us better to distil from observations of population density something

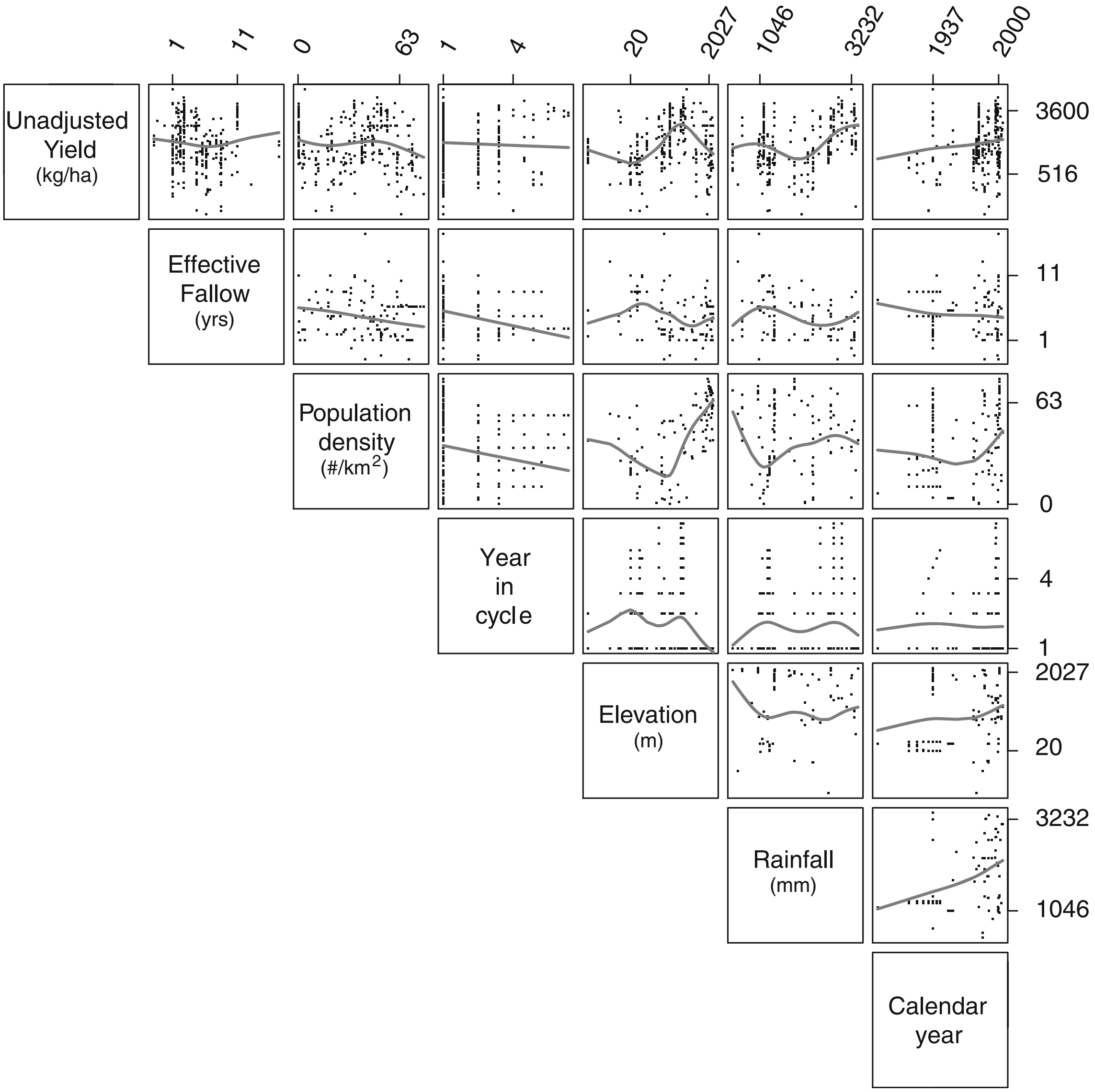


Fig. 3 Pairwise scatter plots of continuous variables, overlaid with cubic splines. The top two rows show *unadjusted yield* and *effective fallow* in relation to their candidate predictors. There is one exception: *year in cycle* is excluded as a predictor of *effective fallow* for reasons described in the main text. The remaining rows of the matrix display relationships between the predictors themselves. All variables have been transformed by the natural logarithm; axis ticks mark the 10th and 90th percentiles of each variable, annotated with values in the original units of measurement (e.g., kg/ha for *unadjusted yield*)

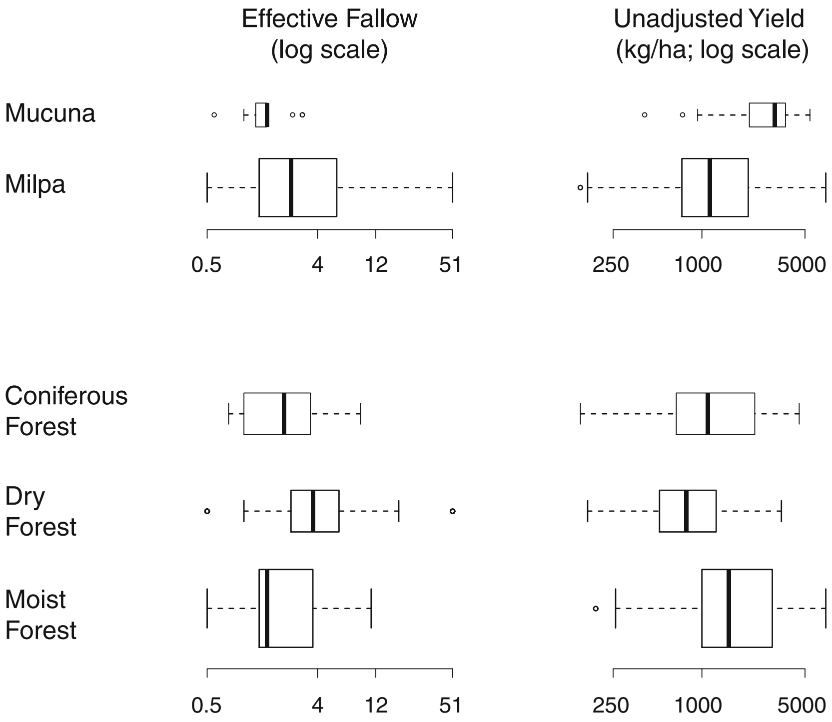
more closely approaching population pressure, the key variable for Boserup (see "Discussion: Boserup in the Milpa").

Model Y examines *unadjusted yield* as a consequence of two pathways of relatedness. The direct effects of *population density,* our focal predictor, and *effective fallow* on *unadjusted yield* are shown as solid arrows. The dashed arrow recapitulates the relationship between *population density* and *effective fallow* from Model M, allowing us to assess the indirect effect of *population density* on *unadjusted yield* through the mediator *effective fallow.*

Finally, Model A extends Boserup's theory to the composite variable *adjusted yield*, which – as described earlier – is the long-term outcome of farmers' land use and planting decisions.

The effects in Models M, Y and A can be estimated by fitting multi-level regression models containing random intercepts for clusters. The technical details guiding this choice of method are given in the Supplemental Materials ("Statistical Modelling"). The significance, directions and magnitudes of these effects will help us understand the extent to which Boserup's predictions hold in this sample. We use basic and custom-designed functions of the R statistical programming language (2013) throughout; details are given below.

Fig. 4 Model categorical variables – *strategy* and *biome* – in relation to *effective fallow* (*left panel*) and *unadjusted yield* (*right panel*). Left to right, our quantitative values for *effective fallow* can be read as running parallel to qualitative descriptors for agricultural intensity, such as multicropping, grass fallow, bush fallow and forest fallow (e.g., Turner II 1976: 80). Variable width, *whisker box* plots following standard R conventions (R Core Team 2013)



Variable Transformations and Selection of Covariates

We transform all continuous variables by the natural logarithm to stabilize variances and achieve compatible scalings. The integer value 1 was added to all values of *population density* prior to transformation to accommodate some low-density cases. Because we expected to include both linear and squared terms for *population density, elevation* and *rainfall* in regression models, we centered their log-transformed versions at sample averages (see Table 1 notes). We continue to call the transformed, centered variables by their original names. Graphical displays are on logarithmic scales but show original linear units of measurement on the axes.

Two goals guide our model-building process. First, we aim to include covariates that, if ignored, could confound relationships between *population density*, *effective fallow* and *unadjusted* or *adjusted yield*. For example, the bivariate plots of Fig. 3 suggest that *population density* and *unadjusted yield* may each be related, perhaps in complicated ways, to *rainfall*. If *rainfall* were causal, affecting both human settlement patterns and farm productivity, it would be misleading to claim a relationship between *population density* and *yield* while ignoring *rainfall.* We therefore control for *rainfall* and other covariates by including them in Models M, Y and A. Stated more formally, we make the focal relationships in the regression models – between *population density*, *effective fallow* and *unadjusted* or *adjusted yield* – conditional on covariates such as *rainfall*.

Our second aim is to build models that achieve a reasonable balance between goodness of fit and complexity. We used the Akaike Information Criterion (AIC) (Akaike 1973; Burnham and Anderson 2002) to measure this trade-off as we considered an increasing sequence of covariates. As Model Y is fundamental to the analysis that follows, we selected covariates for this model and retained them – with modifications described below – for Models M and A. Beginning with linear and squared *population density,* along with *effective fallow*, we added covariates to Model Y, evaluating the resulting change in AIC at each addition. Completeness and symmetry of the covariate set were as important in our selection process as changes in AIC. Although our final models are adequate in view of information theory, we did not aim to minimize AIC over the set of all possible models, but rather to select models that are interpretable and fit the observations well.

Mediation Analysis

Model Y posits that an increase in *population density*, holding other variables constant, may be associated with a change in *unadjusted yield*. But Model Y also offers a second, indirect form of relationship: an increase in *population density* may change *effective fallow,* perhaps negatively, and a change in *effective fallow* may lead to a subsequent change in *unadjusted yield*. Because the relative strengths of these relationships could determine how population growth ultimately affects maize production, we examine this relationship with a mediation model (MacKinnon, *et al.* 2007). See "Mediation Analysis," Supplemental Materials for additional details.

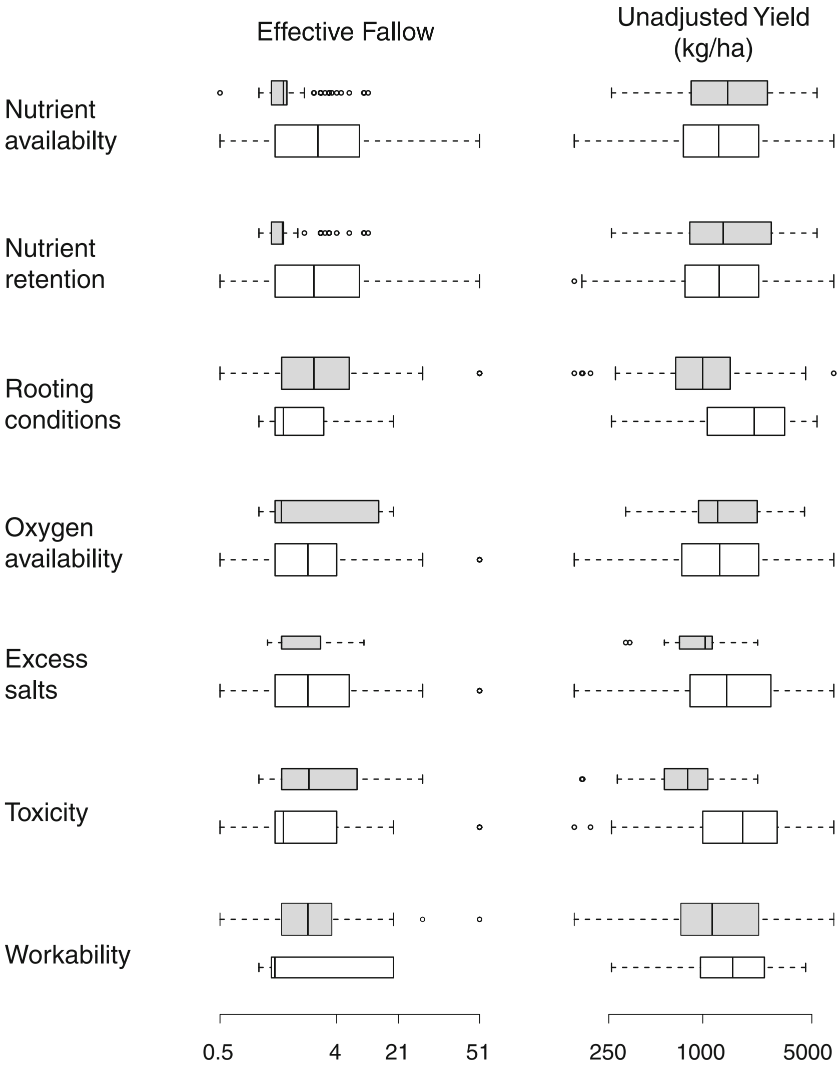


Fig. 5 Categorical model variables – *soil qualities* 1 to 7 – in relation to *effective fallow* and *unadjusted yield. Grey shaded boxes* represent the *severe constraints* category; *open boxes* the *slight constraints* category (see text). Variable width, *whisker box* plots following standard R conventions (R Core Team 2013)

Results

Boserup's Basic Prediction: Model M

We find only weak evidence for a relationship between our focal predictor, *population density*, and *effective fallow*. These variables behave in the direction Boserup predicted, in that shorter fallows are associated with higher densities (Fig. 7; Table 1), but the relationship is not statistically well supported in a model controlling for other determinants of fallow practices.[1] Neither the focal predictor *population density* nor the control covariates of Model M explain variation in *effective fallow* very well in this sample, judging from Table 1. The estimated coefficients are all dominated by their standard errors, and the residual standard deviation is large with respect to the range of the log-transformed dependent variable.

It is challenging to interpret regression models containing many predictors from coefficient tables alone. We therefore use Fig. 7 to summarize the key findings from Model M. The central curve shows the relationship between *effective fallow* and *population density*, conditional on the agricultural, environmental and other covariates listed in Table 1. The curve is concave-downward, and slopes down to the right as expected, but it is shallow overall and the wide shaded bands suggest that statistical uncertainty is high. We generated the lighter grey curve by mapping the regression model of Turner *et al.* (1977 eq. 1) onto the log-log scaling of Model M. Turner *et al.* (1977) analyzed $n=29$ tropical subsistence groups, each having a paired observation of fallow cycle and population density along with agricultural and environmental covariates. In Turner *et al.*, the effect of population density on fallow cycle was consistent across models incorporating different control covariates, and the relationship was statistically well supported.

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[1] A likelihood-ratio test comparing model M to a reduced model, from which *population density* and (*population density*)^2 were excluded, produced the chi-square test-statistic 3.40, having 2° of freedom and *p*-value 0.18. Thus the *population density* terms could be eliminated from model M with little harm to goodness of fit.

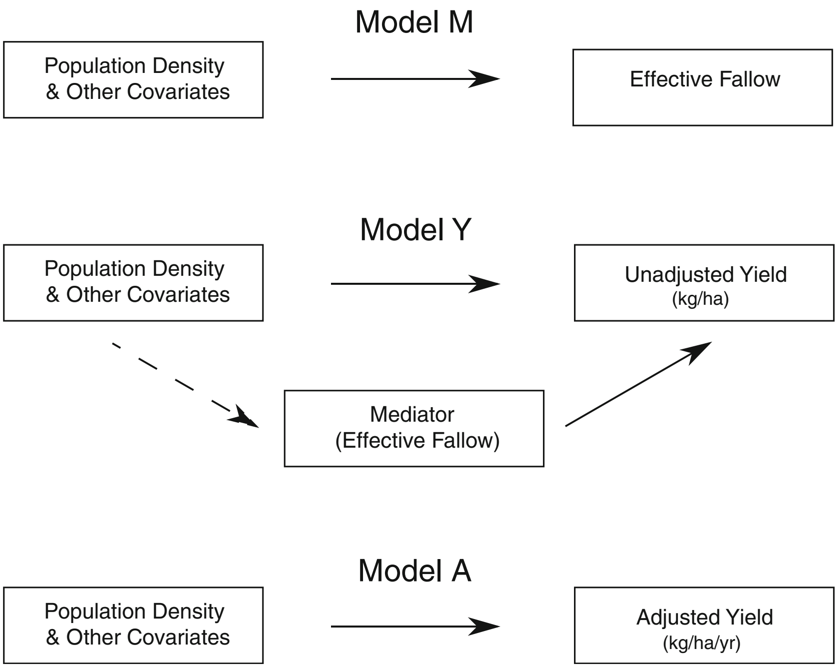

Fig. 6 Three representations of Boserupian predictions assessed by model fitting. See text ("Analytical Approach") for details

Some care is needed in comparing our findings to those of Turner *et al.* (1977). Their sample was global in scope, included a variety of staple crops, and had population densities ranging from one to 233 persons per square kilometer. Ten out of 29 cases had population densities greater than 100/km^2, where the extremes of our sample lie. In Fig. 7, the curve from Turner *et al.* is flat over much of the range of population densities observed in our sample, having a pronounced decline only at the right-hand extreme. At low population densities, the two curves differ only by a level change, reflecting, by our observations, shorter fallow cycles.

Our investigations suggest that *biome* and *strategy* by themselves may be adequate predictors of *effective fallow.* Along with random intercepts for clusters, *biome* and *strategy* produce a simple model (not shown in Table 1) that compares favorably with Model M in terms of information criteria.[2] The predictors of the simple model behave as might be expected in light of Fig. 4: *dry forests* have longer estimated fallows than *moist* or *coniferous forests,* and *milpa* fields have longer fallows than *mucuna.* The residual standard deviation, which reflects unexplained variation in *effective fallow*, is roughly the same in Model M and the simple model we describe here (0.68 and 0.70, respectively). This quantity is large compared to the estimated effects, suggesting that accurate prediction of fallow practices in traditional Mesoamerican maize cultivation remains a challenge.

Unadjusted Yields: Model Y

Population Density and Unadjusted Yield

We find a parabolic concave-downward relationship between *population density* and *unadjusted yield* (Fig. 8; Left panel). Estimated *unadjusted yield* is relatively low when *population density* is low; it peaks at intermediate population densities and then declines as density increases. The coefficient of (*population density*)^2 in Model Y is negative and large in magnitude compared to its standard error (Table 1). Thus the downward concavity is statistically well supported, even in a model including many other predictors of *unadjusted yield* along with random intercepts for clusters. Although this curve is tilted downward to the right, suggesting that the lowest yields are at the highest population densities, this aspect of the trend has weaker support.

The Mediator, Effective Fallow

The evidence for an indirect effect of *population density* on *unadjusted yield* via the mediator *effective fallow* is weak in this sample (Table 2). For example, one of the larger effects in Table 2 (corresponding to $D=5$, $D+\delta=100$) reflects the average difference in *unadjusted yield* that would occur if *population density* were held fixed at 5 persons/km^2 over the sample, while changing each observation of *effective fallow* to the

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[2] The simple model contains *biome* as a predictor and is therefore not nested in model M; AIC is then used for model comparison. AIC=680 for the simple model, compared to 688 for model M. The difference is moderate in view of information theory, but the simple model having lower AIC is preferred.

Table 1 Model parameter estimates for population density and covariates

	Model M *Effective fallow* Estimate (SE)	Model Y *Unadjusted yield* Estimate (SE)	Model A *Adjusted yield* Estimate (SE)
Geographical covariates			
Population density	−0.08 (0.07)	−0.03 (0.06)	0.00 (0.09)
(Population density)^2	−0.05 (0.04)	**−0.11 (0.03)**	−0.04 (0.05)
Agricultural covariates			
Effective fallow		−0.01 (0.05)	
Strategy *mucuna*	−0.24 (0.18)	0.08 (0.16)	**0.51 (0.21)**
Effective fallow * *mucuna*		0.24 (0.26)	
Year in cycle		**−0.47 (0.09)**	
Year in cycle * *mucuna*		**0.58 (0.12)**	
Harvest season *second*		**−0.50 (0.12)**	
Environmental covariates			
Elevation	0.06 (0.07)	−0.06 (0.05)	−0.05 (0.08)
(Elevation)^2	0.02 (0.02)	−0.03 (0.02)	−0.02 (0.03)
Rainfall	−0.20 (0.20)	0.02 (0.15)	0.19 (0.23)
(Rainfall)^2	−0.18 (0.41)	**1.24 (0.32)**	**1.24 (0.49)**
Soil constraints: *Nutrient availability*	−0.17 (0.28)	0.23 (0.20)	0.28 (0.31)
Nutrient retention	−0.07 (0.30)	0.23 (0.21)	0.12 (0.33)
Rooting conditions	0.14 (0.24)	−0.21 (0.20)	−0.03 (0.30)
Oxygen for roots	0.11 (0.35)	0.31 (0.28)	0.33 (0.45)
Excess salts	−0.73 (0.52)	−0.34 (0.42)	0.54 (0.65)
Toxicity	0.41 (0.31)	**−0.76 (0.27)**	**−1.20 (0.39)**
Workability	0.17 (0.26)	0.35 (0.21)	−0.05 (0.32)
Other covariates			
Calendar year	0.10 (0.08)	**−0.20 (0.06)**	**−0.31 (0.09)**
Intercept	0.44 (0.37)	**7.96 (0.28)**	**7.09 (0.44)**
Standard deviations			
Cluster	0.29	0.34	0.46
Residual	0.68	0.38	0.65
Sample size	297	297	278

Coefficient estimates (Estimate) and standard errors (SE) for the predictors in Models M, Y and A. Numeric predictors (*population density*, *year in cycle*, *elevation*, *rainfall* and *calendar year*) have been transformed by the natural logarithm, along with responses *effective fallow, unadjusted yield* and *adjusted yield*. Variables in both linear and squared forms were centered after log transformation to facilitate computation and interpretation of coefficients: the centering values are 2.22 for *population density*, 5.16 for *elevation* and 7.41 for *rainfall*. See "Sample Preparation" in Supplementary Materials for further details. Empty cells are as follows: *Year in cycle* is excluded as a predictor of *effective fallow* because of its intrinsic relationship to *years cropped* (see "Agricultural Variables" in Supplementary Materials). *Effective fallow* and *year in cycle* are excluded as predictors of *adjusted yield* to avoid similar circularities. *Harvest season* is excluded because it is relevant only to *unadjusted yield*. Coefficients attaining conventional statistical significance (for which the null-value zero is rejected at $p<0.05$) are shown in bold. The sample size for model A is smaller than for models M and Y because the calculation of *adjusted yield* required that we omit some cases (see Table 2 note)

value it would take if, hypothetically, *population density* were 100 persons/km^2. This assumes a large change in *population density*, but the estimated change in *unadjusted yield* is small [a proportional reduction of $\exp(-0.02)=0.98$]. The statistical support for this effect, as well as the others in Table 2, is lacking: in all cases the 95 % confidence intervals contain the null value zero. Broadly speaking, the indirect effects of *population density* on *unadjusted yield* – whatever they may be – do not appear to involve *effective fallow* in a meaningful way.

Other Predictors of Unadjusted Yield

Agricultural and environmental covariates reliably associated with maize *unadjusted yields* can be evaluated in Table 1. Significant negative coefficients for *year in cycle* and *harvest season* indicate, respectively, that *milpa unadjusted yields* are lower over successive years of planting in the same field, as well as for the second harvest within a year. Positive coefficients for the *strategy mucuna* and the interaction *year in cycle * mucuna* indicate that successive year declines are not

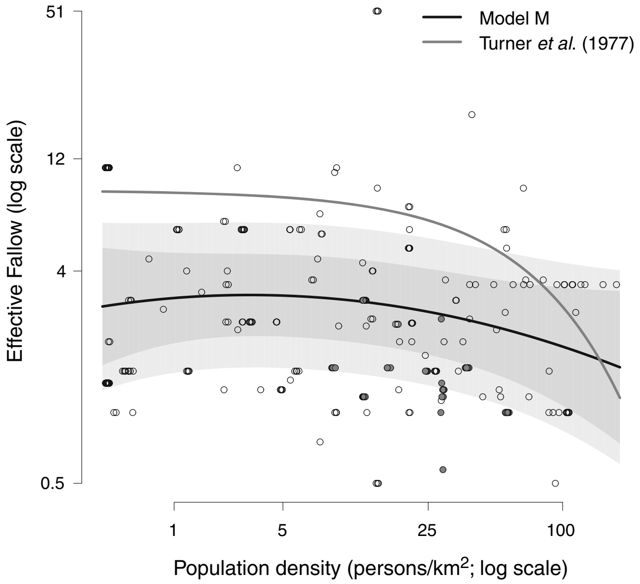

Fig. 7 *Effective fallow* as predicted by *population density* (Model M), conditional on covariates. Also shown are the results from Turner *et al.* (1977). *Dark shading* indicates an approximate 95 % confidence band for the Model M curve; *light shading* indicates an analogous band for prediction of clusters (see section "Statistical Modeling" in Supplementary Materials). The fixed covariates of the conditional model are *milpa strategy*, *elevation*, *rainfall* and *calendar year* (each held at sample averages), and *Soil Constraints* (held at modal values). Open and filled symbols show *milpa* and *mucuna* cases, respectively; the symbols have been jittered slightly in order to separate observations which otherwise would overlap. Straightforward calculations transform Turner's variables (population density and base-10 log of agricultural intensity) into the log-log scaling of Model M. Turner's dependent variable, agricultural intensity, is the inverse of our *effective fallow* (expressed as a percentage), assuming one crop per year

observed in *mucuna* fields. Positive coefficients for *rainfall* and (*rainfall*)^2, the latter significant, imply a concave-upward relationship between *rainfall* and *unadjusted yield*, with particular gains in *unadjusted yield* as *rainfall* increases above 1650 mm annually[3] (Fig. 3). The complicated relationship between *unadjusted yield* and *rainfall* suggested by the cubic spline in Fig. 3 is not supported by model selection: we examined but did not find a significant advantage to model fit from including interactions of *rainfall* and (*rainfall*)^2 with *strategy*.

On average, *unadjusted yields* on soils with some degree of *toxicity* are a fraction exp(−0.76)=0.47 of those on non-toxic soils (toxicity as assessed in HWSD Q6 encompasses soil deficiencies related to excessive calcium carbonate and gypsum). A secular decline in *unadjusted yields* from 1931 to the present is indicated by the negative coefficient of *calendar year*. The effect size is small relative to those for *year in cycle*, *year in cycle * mucuna*, *harvest season second* and, especially, (*rainfall*)^2, but otherwise we do not have a good explanation for this observation. Interpretation of each of these effects is encumbered by the assumption that all other covariates remain constant – a steep requirement for predictors of *unadjusted yield* tied together in space and time.

The relevance of clustering in the sample is demonstrated by the intra-class correlation coefficient (ICC), calculated as the ratio of the cluster variance to the total variance: $0.34^2/(0.34^2+0.38^2)=0.44$. Broadly speaking, 44 % of the total variance in *unadjusted yield* (variation unaccounted for by the predictors of model Y) is cluster-to-cluster variance. We understand this to mean that unique growing conditions and practices specific to clusters – which are aggregations of cases in space and time – have significant impacts on *unadjusted yield*.

Adjusted Yields: Model A

The conditional relationship between *population density* and *adjusted yield* is noticeably flattened in comparison to the relationship between *population density* and *unadjusted yield* (right – vs. – left panels of Fig. 8). Statistical support for *population density* and (*population density*)^2 as predictors of *adjusted yield* is weak.[4] *Adjusted yield* does not seem to be sensitive to changes in *population density* after controlling for cluster baselines and other covariates.

Adjusted yields on *mucuna* fields are on average exp(0.51)=1.67 times as large as on *milpa* fields, all else being equal. (*Rainfall*)^2, *toxicity* and *calendar year* play similar roles in predicting *adjusted yield* as they do for *unadjusted yield. Toxicity* has a notably larger negative impact; *calendar year* is also larger. Finally, cluster-to-cluster variance is lessened but remains a large portion of the total variance in *adjusted yield* (ICC=0.33).

Discussion: Boserup in the Milpa

With antecedents in the work of German and Russian economists and geographers (Grigg 1979: 64–65; Hunt 2000: 253) the Boserup hypothesis has become the subject of a considerable literature (reviews in Brookfield 2001; Giampietro 1997; Grigg 1979; Hunt 2000; Johnston 2003; Netting 1993; Stone 2001; van der Veen 2005). Boserup has been viewed not only as a theoretical upending of Malthus – a view challenged by various analytical reconciliations of his work and hers (see Lee 1986; Netting 1990; Robinson and Schutjer 1984; Wood 1998) – but as an alternative to models of sociocultural evolution that give primacy to technological innovation (Netting 1993: 26–27). Although focused on agricultural

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[3] The critical point of the parabola occurs at approximately *rainfall*= exp(7.41), using the centering value on the log scale (see Table 1).

[4] A likelihood-ratio test comparing model A to a reduced model, from which *population density* and (*population density*)^2 were excluded, produced the chi-square test-statistic 0.71, having 2° of freedom and *p*-value 0.70. Thus as for model M, the *population density* terms could be eliminated from model A with little harm to goodness of fit.

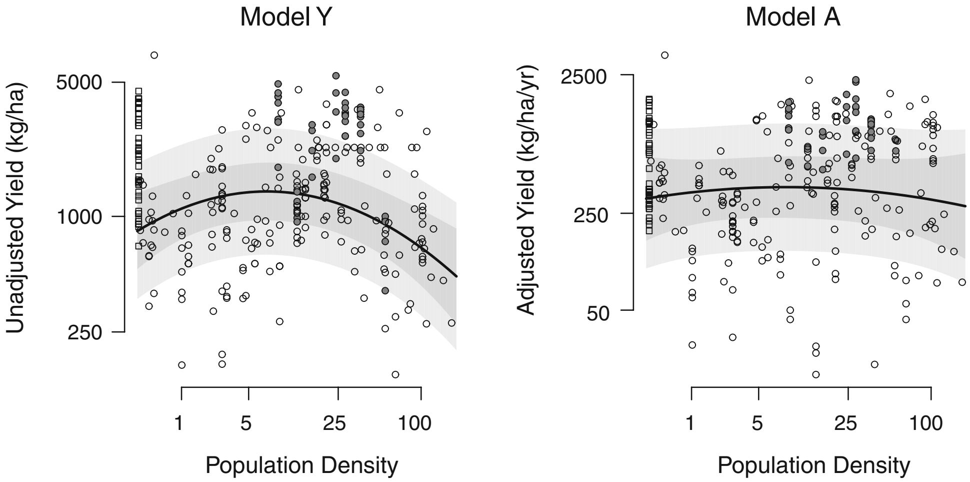

Fig. 8 Model Y *unadjusted yield* (*left panel*) and Model A *adjusted yield* (*right panel*) as a function of *population density*, conditional on other covariates. *Dark shading* indicates an approximate 95 % confidence band for the curve; *light shading* indicates an analogous band for prediction of clusters. The mediating covariate *effective fallow* is held fixed at 1.0 as *population density* varies in the left panel, a value representative of a "multi-cropping" regime (Johnston 2003: 129; Turner II 1976: 80). In the left panel, *year in cycle* is held fixed at the sample average, and *harvest season* is fixed at the modal value, indicating the first season. In both panels, values of the remaining covariates are as in Fig. 7. As described in the section "Statistical Modeling" in Supplementary Materials, our dataset contains spatially and temporally clustered observations, often obtained from the same primary source. These call for multi-level modeling (which we use) or related approaches for similarly-structured data. The 48 observations from Urrutia (1967) are indicated by open squares in both panels. These form the largest cluster in the sample; they provide some of the lowest *population densities* and some of the highest *unadjusted yields* (see Fig. 2). In Model Y, the estimated random effect for this cluster is 0.61; thus the unique baseline *unadjusted yield* (on the natural log scale) for the cluster is approximately two standard deviations above average (Table 1). The observations from Urrutia (1967) would have undue influence in a model for *unadjusted yield* that failed to acknowledge clustering; consequently, Model Y corrects for cluster baselines. In model A, the estimated random effect for the Urrutia cluster is 0.04 and thus the baseline *adjusted yield* for these observations is near the average

development, her emphasis on the role of intensification in driving socio-economic change has had an enormous parallel influence on hunter-gatherer studies (Morgan 2014) and prehistoric archaeology (Morrison 1994).

Determinants of Milpa Maize Productivity

Model Y finds meaningful structure in the data. After excluding biome, it includes most of the predictor variables we were able to assemble as covariates. Six predictors and one interaction have significant effects on *unadjusted yield* in the traditional *milpa* system (Table 1). By contrast, our Model M for *effective fallow* has fewer predictors and none are significant. In Model A, estimating *adjusted yield*, relatively few of the incorporated covariates are significant. We discuss the implications by category of variables.

Geographical Variables

The impact of *population density* on *effective fallow* (Table 1; Model M) is negative, as expected, but small and non-significant. The relationship between *population density* and *unadjusted yield* peaks at an intermediate value of the covariate (Table 1), the Model Y quadratic term (*population density*)^2 being significant. The curve is parabolic, concave downward and tilted slightly down toward the right in response to the linear trend in *population density* (Fig. 8). This result is consistent with successful intensification only across the lower end of the population range. At higher densities, unit area yields of *milpa* production reverse this trend and decline.

When yields are adjusted by agricultural practices to give us *adjusted yield* – compounding two mechanisms by which intensification might take place – neither of the two population predictors [*population density*, or (*population density*)^2] is significant. Thus, we do not find strong support for the most general version of the Boserup theory in the overall dataset. This is not a surprise, as neither of the density variables has a significant relationship to *effective fallow.*

Our conditional results (Fig. 8) show that Model A *adjusted yield* does not suffer the downturn at higher densities seen in the Model Y results for *unadjusted yield*. This suggests that some factor not captured in our predictor variables – labor investment would be a good candidate – helps to maintain *adjusted yields* across the full range of *population densities* in our dataset.

Environmental Variables

Sain and López-Pereira (1999) note that *milpa*-maize in Mesoamerica is grown predominantly on hillsides, suggesting that slope is an important component of the production regime. Our data do not allow us to examine slope; however,

Table 2 Indirect effects (log scale) of *population density* on *unadjusted yield*

	D + δ			
D	1	5	25	100
1	0.00 (−0.02, 0.03)	0.00 (−0.03, 0.03)	0.00 (−0.03, 0.03)	−0.01 (−0.08, 0.05)
5	0.00 (−0.03, 0.02)	0.00 (−0.02, 0.02)	0.00 (−0.03, 0.02)	−0.02 (−0.10, 0.05)
25	0.01 (−0.03, 0.03)	0.00 (−0.02, 0.03)	0.00 (−0.02, 0.01)	−0.01 (−0.05, 0.04)
100	0.02 (−0.05, 0.09)	0.02 (−0.04, 0.10)	0.01 (−0.04, 0.06)	0.00 (−0.02, 0.02)

Indirect effects of *population density* on *unadjusted yield*, through the mediator *effective fallow*, along with 95 % confidence intervals. Rows give the value D of *population density* in the "control" condition; columns give the value D + δ in the "treatment" condition. Basic details about indirect effects are in section "Mediation Analysis" in Supplementary Materials. Indirect effects are estimated by stochastic simulation of potential outcomes using the parametric algorithm of Imai *et al.* (2010). Stated briefly, the algorithm works as follows. At the first stage, potential values of *effective fallow* under the control and treatment conditions are generated for each observation. Potential values for the i^th^ observation under the control condition have the form $\tilde{E}_{D,i}=\mathbf{A}\mathbf{x}_i+B_1D+B_2D^2+\varepsilon$, where $\mathbf{x}_i$ is the column-vector of model M covariates for observation i [excluding *population density* and (*population density*)^2]; B_1 and B_2 are random regression coefficients for *population density* and (*population density*)^2, and **A** is a row-vector of random regression coefficients for the covariates $\mathbf{x}_i$, all obtained from the large-sample multivariate-Gaussian distribution of model M; and ε is a random Gaussian deviate sampled from the model M error distribution. Potential values $\tilde{E}_{D+\delta,i}$ under the treatment condition are generated in a similar way, with D+δ in place of D. At the second stage, potential values of *unadjusted yield* are generated. Under the control condition, these have the form $\tilde{Y}_{D,i}=\mathbf{F}\mathbf{z}_i+G_1D+G_2D^2+H\,\tilde{E}_{D,i}+\varphi$, where $\mathbf{z}_i$ is the column-vector of model Y covariates for observation i [excluding *population density*, (*population density*)^2 and *effective fallow*)]; G_1, G_2 and H are random regression coefficients for *population density*, (*population density*)^2 and *effective fallow*, and **F** is a row-vector of random regression coefficients for the covariates $\mathbf{z}_i$, all obtained from the large-sample distribution of model Y; finally, φ is a random Gaussian deviate sampled from the model Y error distribution. Potential *unadjusted yields* $\tilde{Y}_{D+\delta,i}$ under the treatment condition are generated analogously, with $\tilde{E}_{D+\delta,i}$ in place of $\tilde{E}_{D,i}$. All potential values are in the log-log scalings of models M and Y. The indirect effect on *unadjusted yield* of a change from *population density* D to *population density* D+δ is estimated by averaging the contrasts $\tilde{Y}_{D+\delta,i}$ - $\tilde{Y}_{D,i}$ over the observations i, and over simulated coefficient sets. Our estimates are based on 100 random coefficient sets from models M and Y, with 10 residual-error replicates for each coefficient set

neither *elevation* nor (*elevation*)^2 appear to influence *unadjusted yield* in our sample (Table 1), despite the peak of *unadjusted yield* (~2,300 kg/ha) observed at an *elevation* of 400 m in Fig. 3.

The (*rainfall*)^2 quadratic term has a significant and fairly large positive effect on *unadjusted yield* and *adjusted yield*, but does not correlate significantly with *effective fallow* (Table 1). The significant *rainfall* relationship with both yields comes with a caveat, however. It is important to acknowledge the distinction between *milpa* and *mucuna* strategies, both of which are in the database. The positive correlation between rainfall and yield is largely due to the concentration of the very high yielding *mucuna* strategy (Fig. 2) at the upper end of the rainfall range.

We do not have a compelling explanation for the decline in *milpa* yields at intermediate values for *rainfall* (Fig. 3). It could be that selection for local landraces is more advanced under unusually dry or wet conditions. Or, if we consider *milpa* as a component in a multi-cropping system, perhaps competing cultivars sharing the same field plots represent more of the biomass and potential production at intermediate levels of rainfall.

Of the seven *soil constraints* only one (*toxicity*) negatively influenced *unadjusted yield* and *adjusted yield*. This suggests to us that farmer management practices or the maize varieties used in each location are well adapted to overcome limitations in *soil quality.*

Agricultural Variables

Management practices affecting long-term, *adjusted yields* appear to offset some of the downturn that we observe in *unadjusted yields* at high *population densities* (compare right and left panels, Fig. 8). This is limited intensification in the sense that *adjusted yields* are better maintained over a range of *population densities* than *unadjusted yields*. However, the temporal element of fallowing practices that we are able to observe does not respond significantly to any of our predictors (Model M), nor does *effective fallow* seem to operate as a mediating variable between *population density* and *unadjusted yield* (Model Y). In the case of standard *milpa*, we do observe a significant decline in second season yields, and in successive yields in following years. In contrast, yields of maize fields planted in the *mucuna strategy* are both higher, and do not decline with successive plantings (Table 1).

Intensification can be measured in various ways (Shriar 2000). Because our primary objective is empirical assessment of Boserup's theory in the *milpa* context, we focus on *unadjusted* and *adjusted yield* in relation to population pressure, fallow practices and other covariates. *Effective fallow,* the dependent variable of Model M, incorporates *crops per year*, a key factor in cropping frequency and yet another aspect of intensification (see Shriar 2000: 307–308).

Milpa and Maya Prehistory

Contemporary maize yields are employed regularly by prehistorians to assess the role of subsistence production in the development of Maya population and polities (Cowgill 1962; Ford and Clarke n.d.; Morley and Brainerd 1956; Reina 1967). The results have provoked an enduring mystery. *Milpa* yields would appear to support far fewer people than archaeological evidence suggests lived in the region (Dahlin, *et al.* 2005; Driever and Hoy 1984; Redfield and Villa Rojas 1962; Schwartz 1985); there is a large kilocalorie gap between estimated production and projected consumption and a large literature proposing to bridge it. Proposals on the production side entail greater dependence on root (Bronson 1966) or tree (Puleston 1968) crops, on gardens, hunting and fishing (Wilken 1971), on marine and aquatic foods (Lange 1971), or on intensive substrate manipulation using ridged fields and drainage (Turner II 1974) (summaries in Nations and Nigh 1980; Netting 1977; Turner II and Miksicek 1984). On the consumption side, the suggestion that populations were not as large as has been proposed (Webster 2014; Webster 2007) also would lessen the mismatch.

We make four comments on this debate. Common to each is the observation that earlier investigators drew from a much more limited sample of yield estimates and, perhaps consequently, were unable to develop interpretations based in statistical tools.

Unrepresentative Samples

Maize yield estimates frequently used to make archaeological inferences about the resource base of Classic Maya populations have tended to come from the lower end of our sample range (e.g., Cowgill 1961, 1962; Morley and Brainerd 1956; Nations and Nigh 1980; Redfield and Villa Rojas 1962; Reina 1967; Steggerda 1941; Villa Rojas 1945) (Fig. 2). However, the 10-fold increase (Table S3) in *milpa* median yield estimates, from Reina (1967) to Coe and Diehl (1980), suggests higher prehistoric *milpa* productivity than has been thought possible.

Inter-annual Sample Variation

With a sample that affords a comparative perspective, it is easier to appreciate that individual cases are affected by unique contextual features. Morley and Brainerd (1956), for instance, measure multiple consecutive years of cultivating the same field, noting that their eighth year of experimentation was affected by locusts (likely the same epidemic mentioned by Ewell and Merril-Sands 1987). Lopez Corral (2011) record a prolonged *canícula*, a period of drought during the rainy season that destroyed practically all *milpas* in Puebla in 2009. We do not include this case in our sample, though it represents how far yields can fall when environmental conditions are poor. Intensive resource management and polyculture (Diemont, *et al.* 2006; Nations and Nigh 1980) and the colonization of a new area (Urrutia 1967) correspond to three of the cases in which *milpa*-maize *production* is the highest in our database. Data from Stadelman (1940) also evidence high yields, but should be interpreted with care since he estimates yields in all municipalities from Huehuetenango Department (Guatemala) based on the measurements at one location only. Castañeda (1998) describes features of Huehuetenango pertinent to appraisal of the Stadelman data. Multi-level analysis and model fitting affords us some control over this kind of heterogeneity.

Potential for Intensification

Robust confirmation of Boserup using a *milpa* sample would have given us another possible avenue for bridging the kilocalorie gap in Maya prehistory. Ancient Maya cultivators could have had available to them ready options for intensification of production not evident in the contemporary samples frequently used by archaeologists. For instance, Dahlin *et al.* (2005) report average maize production in Northern Yucatán to be between 250 and 1700 kg/ha but, citing Boserup and intensification, they acknowledge that yields may have been greater in the past. Our analyses suggest this option has limited promise, with a caveat. *Unadjusted yields* rise at the lower end of contemporary population density but then fall as density continues to increase. *Adjusted yields* appear to be intensified at the upper end of our population range only to the degree of preventing a significant downturn (Fig. 8). Within the limits of our sample and covariates, model-fitting and the environmental controls afforded by conditional analysis shows us that *adjusted yields* can be maintained but not increased across a wide range of population densities. The caveat is that we are not able to include labor in our analysis. It remains possible that labor intensification in prehistory had more scope for increasing yield than the factors we analyze, through use of technologies like water control systems, terracing and raised field agriculture (references in Kennett and Beach 2013).

Local Production Estimates and Predictor Comparisons

The point estimates of yields used by archaeologists working in the Maya region may be misleading in particular cases because they are independent of context. Model fitting over a large sample of contexts gives us a means of transcending this shortcoming. Yield estimates produced by Models Y and A after incorporating local values for predictor variables are more likely to be representative of local production potential, with the added advantage of estimating error ranges. Regression models also facilitate hypothetical assessments. For instance, Model Y estimates indicate that *unadjusted yield* at the third *year in cycle* at a population density of 25 persons/km^2 using *mucuna* would be around 1,750 kg/ha, while the figure for *milpa* would be 850 kg/ha.

Analytical Approaches in Ecological Anthropology Research

Features of the methods we adopt are worth emphasizing for their potential importance in similar kinds of comparative analysis drawing on ethnographic data.

Matching Analyses to Data Peculiarities

Any large dataset assembled from ethnographic reports will feature information of uneven precision, represented by continuous as well as coarsened categorical variables, and containing different levels of clustering and aggregation that produce a mosaic of independent and dependent observations. We have taken a simple principled approach to these problems by inclusion of random intercepts for clusters, or groups of observations aggregated in space and/or time, and generally reported in the same primary source. Random intercepts accommodate dependencies between clustered observations, as well as correct for baseline differences between clusters.

Mediation Analysis

Mediation analysis allows us to estimate the effect of a focal predictor, here *population density,* on *unadjusted yield,* both directly and indirectly, the latter via the mediating variable (*effective fallow*) (Fig. 6). Our analytical design included the possibility of an indirect effect because the causal sequence *population density* → *effective fallow* → *unadjusted yield* is a plausible pathway for Boserupian intensification. However, given that *population density* is a weak predictor of *effective fallow* (Table 1: Model M) and *effective fallow* is a weak predictor of *unadjusted yield* (Table 1: Model Y) we are not surprised that the indirect effect is weak in our particular sample. We hypothesize that other variables related to labor and field management, unavailable in our dataset, mediate the relationship between *population density* and *unadjusted yield*.

Testing Boserup with Statistical Controls

Agrarian output is a product of complex geographical, environmental and anthropogenic causation; comparative study that does not control for such covariates risks confounding causes. This is a problem in the literature evaluating the Boserup theory, much of which assesses single predictor correlations between population density and fallow or population density and yield. Without controls a false result can be created or a real one masked by intervening variables; population density might increase and fallow length decline across a sample for ecological reasons having nothing to do with population pressure. A related problem is the assumption that increasing population density implies increasing population *pressure*, the latter the primary source of causation in the Boserup theory. This frequently is assumed because independent means of evaluating the concept of pressure are absent. However, by controlling for covariates that affect yield, we better secure the claim that population density is a suitable proxy for population pressure. All else equal – where the "all else" are conditions known to affect environmental productivity – increasing density should imply increasing pressure.

Our use of multilevel modeling and mediation analysis represents an attempt to better address these complexities. Figure 8 represents our most synthetic appraisal of the Boserup hypothesis. The left panel, the predicted relationship between *unadjusted yield* (kg/ha; model Y) and *population density* conditional on all other covariates, shows that yields rise gradually to a peak at 7 persons/km^2 then decline for the greater part of the density range. Intensification of milpa/maize production by *unadjusted yield* appears to be effective only at relatively low population densities; further increases in population density have a negative effect. This is expected if, for instance, soil fertility drops with repeated use of land, as reported for Los Tuxtlas (México) (Eilittä, *et al.* 2004; Negrete-Yankelevich, *et al.* 2013) or for Paso (Costa Rica) (Barlett 1977), a possibility acknowledged by Boserup (see Grigg 1979: 69).

After adjusting long-term, farmstead level yields (kg/ha/yr; Model A) to the full agricultural cycle including fallow, we find somewhat improved but still modest support for Boserup's hypothesis on intensification (Fig. 8; right panel). The conditional model for *adjusted yield* is slightly concave downward, with a peak at 8 persons/km^2 and minor declines for population below and above this density. Fallow adjusted maize production can be sustained but not significantly increased as population pressure increases.

Milpa and Contemporary Subsistence

Sain and López-Pereira (1999) show that increases in maize production in Mexico have occurred in intensive systems while in the rest of Mesoamerica and adjacent regions such increases are due to the use of extensive systems, or what we have termed *milpa*. They note that most smallholders cultivating maize are located in hillside areas with low productive potential, while the commercially-oriented producers dominate in higher-yielding valleys. Large numbers of households are affected. In 2005 the FAO (FAOSTAT 2011) estimated that México, Guatemala, El Salvador, Belize, Honduras, Costa Rica, Nicaragua and Panamá had 144,289,000 inhabitants, of which approximately a quarter depend directly on agriculture for subsistence. In their worldwide analysis, Rudel *et al.* (2009) find that increases in crop production from 1970 to 2005 are mostly attributable to agricultural intensification (18–47 %), rather than to expansion of the area cultivated (0.6–32 %). Further analysis by Gibbs *et al.* (2010) shows that impacts from increasing demand for agricultural products (1980 – 2000) occur largely in tropical forests regions of the developing world, areas especially rich in biological and cultural diversity (de Ávila 2008). These tend to be regions in which the practice is *milpa* or *milpa*-like systems of cultivation, Mesoamerica an example.

These observations illustrate the importance of understanding how extensive farming systems affect and are affected by geographical, environmental, agro-economic and political factors. Boserup's theory of intensification, updated and amended to include factors such as environment, market pull and off-farm employment, provides a useful framework for undertaking that investigation (Pfeffer, *et al.* 2005). Food security and minimization of environmental impacts are at stake. Analyzing land tenure changes in Costa Rica, Bertsch (2006) finds that pressures resulting from urbanization and farmer indebtedness override land use planning: land passes from small to larger owners, and increases in production are mostly associated with crops grown for export. Similar changes occurred in Guatemala, El Salvador, Mexico and Nicaragua.

Dahlin *et al.* (2005) estimate that a Maya family of five can consume a little more than 1000 kg of maize per year. According to our average fallow-adjusted maize yields (Model A), such family sizes could have been sustained in the past even at high population densities, provided that they had access to roughly 4 ha of land over the full agricultural cycle. Still, additional subsistence strategies might be needed or adopted in order to cover farmers' nutritional or economic needs. Farmers from southeast México started doing apiculture after a long drought and plague of locusts attacked their crops in 1940 (Ewell and Merril-Sands 1987): the primary source of cash income for Huastec Mayans is the sale of sugar (Alcorn 1989). Mixed subsistence strategies also have been suggested by Dahlin *et al.* (2005) and Feinman *et al.* (2007) for the Northern Yucatán and the Valley of Oaxaca, respectively, where soil and rainfall conditions would appear not to support adequate maize production. While we have confined our analysis to maize, we note that intensive use of other plants, craft production and exchange could have compensated for recurrent or periodic maize deficits.

Indigenous agro-ecological systems like *milpa* can be quite sustainable (Ford and Clarke n.d.). Smallholders produce food for consumption and exchange through the careful management of fallow, manipulation of soil, regulation of water supply, diversification of crops and protection of plants and animals (Netting 1993). An example is found within several indigenous (e.g., Maya, Nahua, Zapotec, Mixtec, Otomi, Lacandon) groups in Mexico (Nigh and Diemont 2013; Toledo, *et al.* 2003), that have been able to increase or maintain their populations between 1980 and 1990 by means of intensified environmental management.

As observed in this analysis, crop scientists and farmers in Mesoamerica have found that intercropping maize with *Mucuna* sp. (Adans) increases yields (Buckles, *et al.* 1999). *Mucuna*, a vigorous climbing annual legume of Asiatic origin, is well known for its ability to hold soil moisture and fertility. However, adoption of the *Mucuna*-maize system remains limited and experience mixed, either successful (Pool Novelo, *et al.* 1998; Triomphe and Sain 2004) or unsuccessful (Eilittä, *et al.* 2004). Our analysis suggests that *mucuna* yields are high and sustainable under continuous cropping, but that this result depends on high levels of precipitation.

Caveats and Reservations

We present an ambitious analysis aware of its shortcomings. Although they are central elements in the Boserup theory, our ethnographic dataset does not allow us to assess the role of labor investment or technological intensification. We likewise do not assess the degree to which recent developments such as market pull or off-farm employment, rather than population pressure, might stimulate or retard intensification. Data on these market factors are unavailable in most of our sources. We also do not include in our analysis the potential effect of maize landraces on yields (see Wellhausen, *et al.* 1957: for a detailed discription of maize races in Central America). Our results may be affected by the coarseness or low resolution of some of our data. For instance, many of our soil covariates may have failed to reach significance because they represent regional, not field-level, assessments. Working at a finer scale, Ford and Clarke (n.d.) find that slope, drainage and soil quality do a good job of predicting prehistoric settlement density, presumably reflecting local agricultural productivity. In some cases our best measure of population density averages over an area much larger than a village and consequently it may not accurately represent the local conditions actually facing village-level managers of *milpa* production. More generally, the weak support we find for the Boserup hypothesis may be due in part to our decision to restrict the analysis to a single, albeit quite broad category of subsistence production, *milpa*. To this we would counter that even within this category, our Model M prediction is able to draw from a wide range of values for *effective fallow* (Fig. 3) and its covariates, suggesting we have conditions for a fair test.

Conclusions

Assembling data from original research reports on maize yields accumulated over almost 80 years of fieldwork in Mesoamerica and adjacent areas, we develop three predictive models for testing Boserup's population pressure, intensification hypothesis in the *milpa*. We implement analytical approaches that properly deal with heterogeneity, clustering and related features of the sample. We present results controlling for a wide variety of covariates in order to better represent population pressure using measures of population density, and to better isolate confounding factors that affect fallow practices and yield.

The Boserup hypotheses receive only limited support in our analysis. In Model M, predicting *effective fallow* from covariates, *population density* is not significant. In Model Y, combining the direct effects of *population density* and a mediation pathway through *effective fallow*, *unadjusted yield* does not change significantly in relation to the linear term *population density*, although the quadratic term imparting a parabolic downward shape to the relationship is significant. In Model A, predicting fallow adjusted yields, neither the linear nor quadratic form of *population density* is significant. Model A (Fig. 8; right panel) reveals that the *adjusted yield* can be sustained between 280 and 390 kg/ha/yr across the sample range of population densities.

Model A also predicts that implementation of an agricultural strategy like *mucuna* can significantly increase the amount of maize that can be grown. A reduction of fallow combined with intensive management through weeding and mulching, is more in accord with Boserup (Johnston 2003). Further study of the precipitation requirements required for successful implementation of the *mucuna* strategy will be important to assess this.

Finally, the predictive power of the models we present can be employed for understanding prehistoric agricultural systems used by the Maya and may help to solve the conundrum of how Classic Period Maya populations were fed. Our results suggest that *milpa* productivity can sustain higher populations than previously thought. This helps narrow the gap between agricultural potential and population estimates for the Maya region during the Classic Period, even without invoking more intensive subsistence strategies known to exist (Kennett and Beach 2013). They also help us to understand the conditions under which traditional slash-and-burn agriculture (*milpa*) can be sustainably implemented in the present and into the future. The latter is important for demystifying the presumed adverse environmental impact of burning, an important topic of economic and political debate (Eastmond and Faust 2006; Nigh and Diemont 2013), especially for the large numbers of households in Mesoamerica who rely on these traditional subsistence practices.

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