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Tree Felling with Stone Axes: Pre-Bending Matters but Feller Sex Does Not

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Abstract: Based on recent insights about intensive soil husbandry by some Neolithic farmers combined with the required techniques for efficient use of stone tools, this research questions the emphasis in the experimental archaeology literature on felling of large trees by stone-axe-wielding males working alone. To reflect conditions after the short fallows now thought to have been favored by farmers using stone tools, young (8–12 years) and small (3.5–5.6 cm diameter) *Quercus hemisphaerica* (laurel oak) trees were felled in this study by both male and female participants. Felling with a stone axe required an average of 75 more strokes than for felling a similar sized tree with a steel axe. One novel finding in this study is that when the *Quercus hemisphaerica* (laurel oak) saplings were bent over/tensioned by a co-worker, the predicted numbers of felling strokes declined by 123 (73%) for stone axes and by 15 (72%) for steel axes. We also observed no effect of sex on felling efficiency with stone axes. These results suggest that stone-tool wielding farmers of both sexes worked together to clear trees from their fallowed fields.

Keywords: experimental archaeology; *terra preta*; swidden agriculture; anthropogenic dark earths

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1. Introduction

The felling of large trees with stone axes has attracted attention from ethnographers and experimental archaeologists for well over a century (e.g., [1]). More than a dozen replicative or 'imitative' experiments (reviewed by [2]) consistently report that much more time and energy are required to fell trees with stone than with bronze, iron, or steel axes (but see [3]). Less attention has been paid to the felling of small trees because it was assumed that long-fallow swidden agriculture was practiced prior to in situ development or introduction of metal tools. This assumption is increasingly called into question due to recognition of the difficulty of felling large trees with stone axes (e.g., [4]) coupled with burgeoning research on Anthropogenic Dark Earths (ADEs) in South America (i.e., hortic anthrosols or *terra preta do índio*; e.g., [5,6]), and elsewhere in the tropics (e.g., [7]).

Even with fallow periods of only a few years, tree root sprouts, stump sprouts, and colonizing saplings still must be felled, which is an arduous task with a stone axe. For insights into short-fallow Neolithic swidden agriculture, we compared the felling of small diameter trees using stone and steel axes but added a pre-bending treatment. We reasoned that if fellers worked as teams, one person could bend over the small trees while the other chopped the tensioned surface, thereby benefiting from shortened critical crack lengths in pre-stressed structures [8].

The physics of tree felling can be described in terms of the elastic behavior of wood under stress (i.e., force applied) and strain (i.e., changes in length; [9]). In standing tree stems, lines of equal stress run vertically, parallel to the wood grain and vascular tissues. When felling a tree, mechanical failure ensues when the axe head penetrates the stem to the depth at which the remaining wood cannot support the tree. Beyond this depth, known as the critical crack length, cracks propagate through the stem catastrophically. Pulling the stem increases tensional stress near the convex surface, which reduces the critical crack length [8] and should reduce tree felling time and effort. We hypothesized that this benefit is enjoyed both by stone and steel axe wielders, but the relative benefit would be greater for the former.

Given the high breaking strength and potential sharpness of steel coupled with the great force generated by using upper body strength when chopping, experienced and muscular steel axe wielders can cut through wood rapidly. In contrast, stone axe heads fracture easily and dull rapidly if knapped to a sharp edge; hafts are also likely to loosen or break under severe stress. As explained in detail by Jørgensen [3], in contrast to the full body motion of steel axe wielding, felling trees with stone axes is most effectively accomplished with numerous short strokes made at steep angles to the stem; the vertically oriented wood fibers are peeled apart rather than being cut across (Figure 1). Based on the technique required for stone axe use and the few available descriptions of roles in Neolithic agriculture [10,11], we expected no difference between males and females in felling efficiency with stone axes. We tested these hypotheses with a factorial experiment in which male and female volunteers used stone and steel axes to fell small trees, half of which were bent over while being chopped.

Figure 1. *Quercus hemisphaerica* (laurel oak) sapling felled with a stone axe hafted to a *Ostrya virginiana* handle with a bicycle inner tube showing the effects of a typical cut.

2. Materials and Methods

In an abandoned agricultural clearing in Gainesville, Florida, we felled 8–12-year-old laurel oak (*Quercus hemisphaerica*) stems that were 3.5–5.6 cm dbh (diameter at 1.3 m). Each tree was felled with either a stone or steel axe with or without tensioning the stem using a 2 × 2 factorial design. Each participant felled four trees of similar size, one tree in each of the four felling treatments, with treatment order determined at random. Stems were tensioned by a co-worker who reached up, grabbed the stem at 2–3 m, and pulled it over to 35–45° from vertical. The male (n = 12) and female (n = 8) participants ranged in age (14–53 years), body mass (48–99 kg), and tree felling experience, which we described using a 5-point scale in which "1" represented minimal experience (see Supplementary Materials for all the data). Experience scores were assigned on the basis of interviews with the fellers and researcher judgement based on observations of their practice use of the steel axe. Felling times and number of strokes were recorded starting from when the first stroke landed and ending when stem failure occurred, as indicated by audible cracking and rapid change in stem angle. Before commencing their experimental felling, each participant practiced the shallow angle shaving stroke recommended for stone axe use [3] and also practiced with the steel axe.

Two stone axe heads were knapped from brown chert from Polk County, Florida to resemble specimens from the Florida Museum of Natural History (FLMNH A7087). The heads weighed 0.4 kg and 0.6 kg and were 16.9 cm and 17.5 cm long, respectively. Over the course of the study, we tested different handles and hafting techniques, but each subject felled their four trees with the same axe. Initially we hafted the heads to the split ends of 68 cm and 70 cm long handles fashioned from saplings of hop hornbeam (*Ostrya virginiana;* Figure 1). We then made celt axes by inserting the same stones into holes bored in 70 cm long pignut hickory (*Carya glabra*) shafts; the bored end of the handle corresponded to the root crown portion of the saplings to reduce the likelihood of splitting. Despite the importance of hafting (e.g., [12]) and unlike other researchers who attempted to replicate Neolithic hafting techniques [3,13], we hafted with a combination of leather (not rawhide) and strips of bicycle inner tube but without adhesives (e.g., [14]). When re-hafting was necessary mid-trial, the time required was not included in felling-time measurements. Head breakage did not occur, but resharpening was necessary after 3–4 trees were felled. The steel axe (Fiskars Pro 28") was 71 cm long and weighed 4 kg; the cutting edge was 9 cm long and was frequently sharpened.

We examined the effects of axe type and tree tensioning (i.e., main treatment effects) on number of required axe strokes and felling times using a generalized linear mixed model (GLMM), with a Poisson error distribution and log link [15]. The number of required axe strokes cannot be zero; we checked model results with those from a zero-truncated Poisson model to confirm model accuracy (*glmmTMB* package in R; [16]). We included tree DBH, feller experience, and feller sex as covariates; we also tested for a two-way interaction between axe type and tension treatment (Table 1). Felling times and number of required axe strokes were closely correlated (Pearson's r = 0.84) so we focused on the latter. Individual chopper was included as random effect to account for repeated measures (Figure 2).

Table 1. Regression output from generalized linear mixed model estimating number of required axe strokes.

	Estimate	Std. Error	z Value	Pr(>|z|)
(Intercept)	2.77	0.26	10.78	<0.001
DBH	0.12	0.04	2.82	<0.001
Axe (Stone)	2.09	0.05	41.69	<0.001
Treatment (Tension)	−1.29	0.10	−12.68	<0.001
Sex (Male)	0.13	0.16	0.83	0.41
Experience	−0.10	0.05	−2.13	0.03
Axe (Stone): Treatment (Tension)	−0.06	0.11	−0.55	0.58

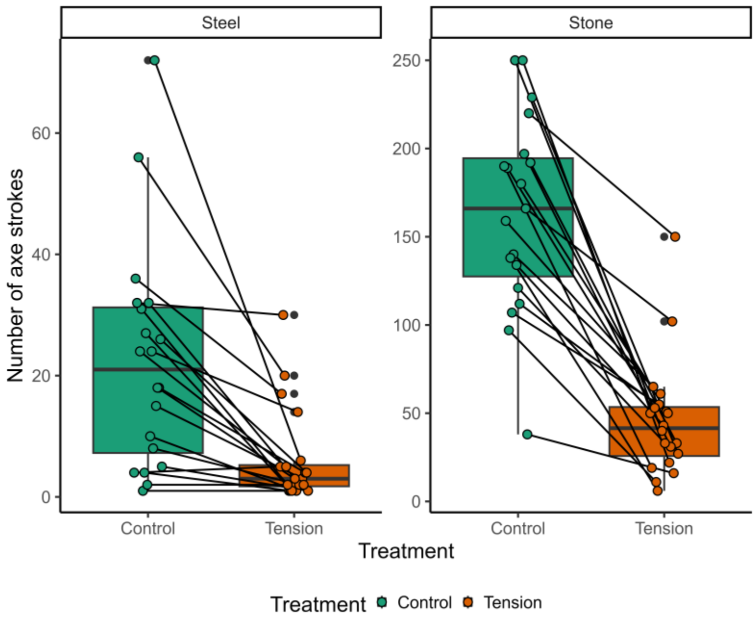

Figure 2. Number of axe blows required to fell 3.5–5.6 cm diameter *Q. hemisphaerica* trees by axe type (stone or steel) and whether or not the stems were pre-tensioned by bending. The lines connect individual choppers. Note the different y-axis scales.

Model diagnostics and figures were created in R version 4.1.0 [17]. All data are available in Table S1 in the Supplementary Materials.

3. Results

The GLMM fit the data well overall—the conditional and marginal psuedo-R^2 values were 0.79 and 0.76, respectively, which we acknowledge should be interpreted conservatively [18]. Results from the zero-truncated Poisson mixed model were nearly identical; therefore, we focused on the Poisson GLMM. The interaction between tensioning treatment and axe type was not significant, but we include it because it is of interest to the study.

Felling even small trees with stone axes is much more laborious than with similar- sized steel axes (Figure 2). For example, an experienced chopper (4–5 on the experience scale) wielding a stone axe would, on average, require an additional 4.25 min and 150 strokes to fell an un-tensioned 5 cm diameter tree (Figure 2, Table 1). As expected, felling times and numbers of strokes both increased with tree stem diameter, but variation among fellers was great. Tree DBH was a significant but weak predictor of felling time; the size effect was especially noticeable for the stone axe with no tensioning treatment (Figure 3).

Bending the trees while chopping reduced the necessary number of axe strokes for both stone and steel tool users, but the benefit was relatively greater for the former (Figure S1). Although the statistical interaction between axe type and tension (vs. control) was not statistically significant (p = 0.58), pre-tensioning reduced a chopper's felling effort by an average of 123 strokes when using a stone axe compared to a 15-stroke reduction when using a steel axe.

The substantial variation in feller efficiency was related to their axe-wielding experience but was not related to their sex (Table 1). Even participants with very little tree cutting experience (classes 1 and 2) required only a few strokes to fell a tree with a steel axe but required up to 515 blows to fell a similar size tree with a stone axe. Our most efficient and experienced participant, in contrast, felled a 4.6 cm diameter tree with a stone axe with only 107 blows in 1.28 min (not including the time needed to re-haft the axe head).

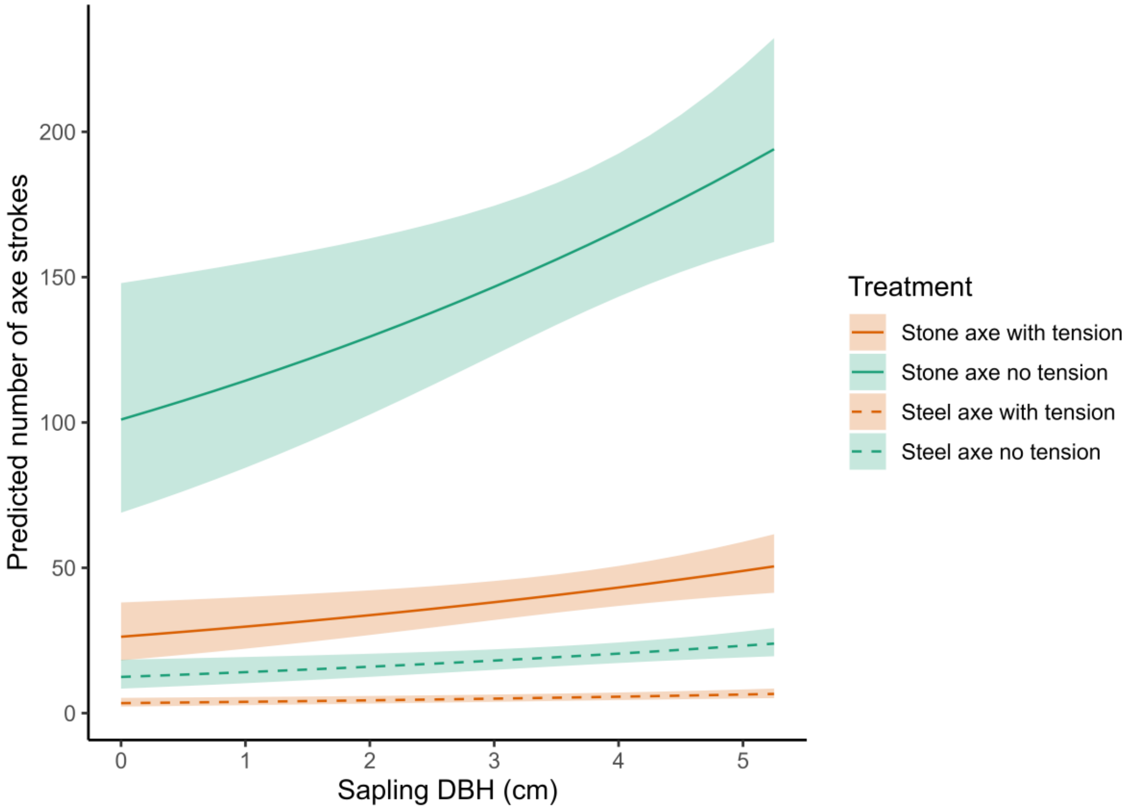

Figure 3. Predicted number of felling strokes from the GLMM (Table 1) as a function of tree DBH partitioned across all treatment and axe type combinations.

4. Conclusions

To the more than a century of experimental archaeology research on tree felling with stone axes this study adds two new insights. First, at least where Neolithic farmers practiced intensive soil husbandry (e.g., adding nutrient-rich organic matter and char while also mulching the surface), which allowed them to rely on short forest fallows, felling the small trees at the end of the fallow period would have been facilitated by working with a partner that bent the tree over. Pre-tensioning stem fibers by bending facilitates tree felling with both stone and steel axes, but the benefit to the former is particularly pronounced. Based on our model, toppling a pre-tensioned 5 cm DBH tree with a stone axe required, on average, 123 (73%) fewer strokes whereas that benefit with a steel axe was only 15 (72%) strokes. An additional advantage of short fallows derives from the higher leaf:wood ratios of small trees and especially sprouts compared to large trees [19]. This means that when small trees are felled and left on the soil surface, they yield more nutrient-rich material with a lower carbon:nitrogen ratio that decomposes more rapidly and is more favorable for soil fertility.

Our other novel finding that feller sex did not affect felling time is understandable given the way stone axes need to be wielded [3], but apparently eluded earlier researchers focused on felling large trees. This finding is also in accord with the written descriptions of Native American farming practices by early European visitors who observed that women carried out much of the work of farming, presumably including the clearing and burning of garden plots [10]. Similarly, amongst the Yir Yoront people of northern Australia where suitable rocks are not locally available, although men historically owned the stone axes they obtained through elaborate and extensive trade networks, these precious tools were mostly wielded by women [11]. We are not sure that even the most efficient of our fellers used the historically accurate technique, but the observed importance of feller experience is also emphasized in the literature of experimental archaeology [20].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f14020202/s1, Figure S1: Predicted number of axe strokes needed to fell a 5 cm diameter *Q. hemisphaerica* stem with a stone versus steel axe felling showing the strong interaction of pre-tensioning the stem; Table S1: Raw data for tree felling study.

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Conflicts of Interest: The authors declare no conflict of interest.

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