Comparing Axe Heads of Stone, Bronze, and Steel: Studies in Experimental Archaeology

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This paper presents inferences based on the results of an experimental project comparing the effectiveness of stone, bronze, and steel axes in felling trees. The study shows that bronze is as efficient as steel for this task, and therefore the two material types can be considered equivalent when comparing technologies. We support the findings of other studies indicating that metal axes are more efficient than stone axes in a number of ways other than effort expended. Other variables that affect tree felling efficiency are discussed. Tree type, tree diameter, and axe type are the most important, but other factors may also be significant. The use of regionally specific estimates for tree felling time is suggested when making cultural inferences based upon experimental data.

Introduction

Archaeologists ask many questions about the technological capabilities of people in the past. They frequently encounter direct evidence of past technologies in the form of tools or other artifacts, and the remains of structures or features built by people using those tools. Understanding the effectiveness of tools or a technological complex often requires a knowledge of how the tools were used and how efficiently they fulfilled their purpose.

One way archaeologists have approached the effectiveness of ancient tools is through replicative or "imitative" experiments (Ascher 1961: 793–795), whereby modern people employ ancient technology in order to simulate the work of past peoples. In spite of Schiffer's (1976: 5–7) criticism of this approach, replication can give insights into various aspects of past societies. For example, experiments can be used to estimate the time required to build structures or clear fields. Archaeologists can use this information to estimate the amount of labor expenditure needed to accomplish certain tasks, to infer how many people such enterprises would require, and to explore the social implications behind the needed labor force, including the social and organizational requirements needed to mobilize a body of laborers. One example is Stephen Lekson's (1984) study of Pueblo Bonito in Chaco Canyon, New Mexico, which demonstrated that building one of the Southwest's most impressive prehistoric structures did not require extraordinary amounts of labor, and therefore a postulated complex social organization is not necessarily indicated.

Much experimental archaeology involving tree felling and axe-use studies has taken place in the past 100 years (Sehested 1884; Smith 1891; Montelius 1906; Pond 1930; Morris 1939; Hyenstrand 1969; Townsend 1969; Bordaz 1970; Heider 1970; Semenov 1964; Saraydar and Shimada 1971, 1973; Kozak 1972; Godelier and Garanger 1973; Coles 1973, 1979b; Coles, Heal, and Orme 1978; Carneiro 1979a, 1979b; Harding and Young 1979; Steensberg 1980; Olausson 1982, 1983; Orme and Coles 1983; Coles and Orme 1985; Jørgensen 1985). Experimental testing of the effectiveness of axes has involved using them in various ways to test plausible functions. The goal of such studies is to learn as much as possible about the capabilities of axes and to get a better idea of their potential as tools. These experiments help researchers to determine the range of uses of an artifact, but do not conclusively determine an artifact's main or sole use. As Schiffer (1978: 236) correctly points out, even in our own society, a tool's stated primary function is certainly not its only use.

This paper addresses two main issues and reaches conclusions based upon an experiment using stone, bronze, and steel axes. First, we compare bronze axes with steel axes in terms of efficiency (as measured by time) in felling trees. Second, we compare metal axes to stone axes in terms of efficiency. We made comparisons in as complete a manner as possible, controlling as many variables with as large a sample as possible, subject to constraints of time, expense, and ability. Where variables could not be controlled, they were noted and their effects were discussed.

Previous Research

Experimentation with stone axes began in the 19th century and determined that stone "axes," whether of chipped or ground stone, were definitely capable of penetrating timber and felling trees (Smith 1891; examples cited in Clark 1945: 68). After the turn of the century, experimentation was uncommon, with the exception of the work of Pond (1930) and Morris (1939), who each felled one small tree. When experimentation with axes was resumed in the 1950s, most notably by Danes (Iversen 1956; Steensberg 1957; Jørgensen 1985), its goals were wide-ranging and its methods more scientific. These experimenters felled large numbers of trees with polished flint axes and recorded much more information than previous investigators. Concern was placed on the ability to clear acres of forests as opposed to felling single trees. Data of this nature allowed researchers to estimate the amount of land that a prehistoric farmer could feasibly clear and cultivate in a given period of time. Tree felling studies also allowed the estimation of labor required for other activities, such as the construction of wood henge monuments (Renfrew 1973), or other building, as in the example of Pueblo Bonito cited above (Lekson 1984).

During the 1960s and 1970s, numerous experiments and observations on tree felling were made. Ethnographers returned from the field with accounts of people making, hafting, and using stone axes or adzes (Carneiro 1974, 1979a; Godelier and Garanger 1973; Heider 1970; Kozak 1972; Steensberg 1980; Townsend 1969). Researchers quantified their trials and created formulae to calculate time required to fell trees (Carneiro 1979a; Townsend 1969). Attempts were made to measure the efficiency of stone axes or adzes against that of steel axes, either by calculating time expended (Carneiro 1979b; Godelier and Garanger 1973; Saraydar and Shimada 1973; Steensberg 1980; Townsend 1969) or oxygen/kilocalorie consumption (Saraydar and Shimada 1971, 1973). These studies also led to the identification of several variables affecting tree felling.

By the late 1970s, experimenters seemed to have thoroughly explored the potential of using stone axes to fell trees. It was obvious that steel axes were better than stone axes at felling, although researchers found that stone axes were capable of felling and clearing even large trees. This apparent exhaustion of the usefulness of experimental tree felling led to a focus on other aspects of the study of axes. The major type of analysis undertaken at this time may be called studies of traces of activity. Traces of activity include evidence indicating the use of an axe to create an item or structure, or evidence indicating the use of a particular type of axe. For example, Deborah Olausson, following in the footsteps of Semenov (1964), studied use wear on flint axes and examined the range of activities they could be used for beyond tree-felling (Olausson 1982, 1983). Other researchers (Coutts 1977; Orme and Coles 1983; Coles and Orme 1985) have studied the marks made by various axe-like tools. Coutts correlated the "morphological characteristics of wood chips freshly cut" (1977: 67) with the types of adzes used in the cutting in an attempt to infer the type of adzes used in the production of archaeologically preserved woodchips. Likewise, Coles and Orme (1985; Orme and Coles 1983) noted axe "signatures" on worked wood "sometimes point[ing] to individual tools" (1985: 27). These studies expanded the field of experimentation with stone axes as they attempted to correlate specific behaviors with archaeological remains, and developed more rigorous scientific controls for such experiments.

Efficiency Comparisons

Six studies have attempted experimental comparisons of steel versus stone (Carneiro 1979b; Godelier and Garanger 1973; Saraydar and Shimada 1971, 1973; Steensberg 1980; Townsend 1969). Three were done on standing trees using steel axes and stone adzes (Godelier and Garanger 1973; Steensberg 1980; Townsend 1969). These studies, which employed time as the yardstick for comparison, showed steel to be between two and four and one half times faster than stone.

The fourth study (Carneiro 1979b) observed the time required to clear one-sixth of an acre (674.5 sq m) of forest with steel axes. Carneiro also verified the results of his earlier study (Carneiro 1979a), demonstrating the effect that tree hardness has on felling time. Carneiro (1979b: 69–70) compared this steel axe data with estimates from the earlier study and found that the relative efficiency of axe types varied with tree size. Steel axes ranged from 10 to 32 times faster than stone axes (Carneiro 1979b: table 6).

The fifth study (Saraydar and Shimada 1971) compared a steel axe to a ground stone axe and measured efficiency by recording oxygen intake and expenditure to calculate kilocalorie consumption with a Kofranyi-Michaelis meter (Saraydar and Shimada 1971: 216). These measurements resulted in a ratio of 6.4:1.0 of steel to stone efficiency in terms of depth cut and a 5.1:1.0 ratio of steel to stone efficiency in terms of kilocalorie consumption per inch of wood cut (Saraydar and Shimada 1971: 217).

Saraydar and Shimada (1973) used the same steel axe and ground stone axe as in their 1971 study (Saraydar and Shimada 1971) to clear plots of land. Each axe was used to clear a 30 ft × 30 ft plot (ca. 9.14 m × 9.14 m), and the energy expended by the fellers was measured with a Kofranyi-Michaelis meter and a Beckman D-2 oxygen analyzer (Saraydar and Shimada 1973: 346). The total time spent was also recorded. They calculated an average kilocalorie per minute expenditure value for each axe based on three sampling periods of five-minute duration, and weighted the plots with respect to each other employing a "wood index" (Saraydar and Shimada 1973: 346–347). This experiment resulted in a ratio of 3.6:1.0 of steel to stone efficiency in terms of time to fell and a 3.3:1.0 ratio of steel to stone efficiency in terms of kilocalorie consumption per inch of wood cut (Saraydar and Shimada 1973: 346).

A review of these efficiency studies raises many questions about how the variables affecting tree felling were controlled. Godelier and Garanger (1973: 210) controlled for circumference (diameter) of the tree, tree type, and individual skill. Unfortunately they felled only eight trees. Steensberg (1980: 34) controlled for circumference (diameter) and for tree type, but he felled only one tree with stone and one with steel. Townsend's (1969: 201) sample, on the other hand, was 91 trees of varying species and size. It is difficult to determine if he controlled for any variables other than species and size, and one wonders how·his results might be skewed. Carneiro (1979b: 58) was able to observe the felling of 25 trees, but he had to estimate the felling time for the remaining 99 trees in his sample, which affected the precision of his results. Saraydar and Shimada (1971: 216), in their first experiment, controlled for the skill level of individual fellers by using the same technique. They also controlled for tree type and did not use the initial or final five minutes of chopping in order to discount effects of fatigue or inexperience. Unfortunately, their sample is one tree cut with steel and one with stone, and their study was conducted in an artificial setting. Although their study demonstrated the relative efficiencies of the two materials, their data are largely inapplicable to real situations, where many other variables affect the final outcome. They clearly demonstrated the greater efficiency of steel, yet the data are of little use to the researcher wishing to estimate labor costs accurately. Their second experiment (Saraydar and Shimada 1973) was more "naturally" set and again controlled for the effects of fatigue or inexperience by employing an average rate, but did not control for tree type.

These comparisons of stone tools and steel axes can help in the explanation of the practical reasons behind a switch to the use of steel axes by "Stone Age" peoples when they gain access to them, but for many parts of the Old World this comparison is often inappropriate, as the transition from stone to steel was usually interrupted by bronze (if not also copper). Surprisingly, there has been little published experimentation with bronze. The few references to bronze axe experimentation in the literature appear to be solely associated with John Coles' (and colleagues') work on the Somerset Levels (Orme and Coles 1983; Coles and Orme 1985). In *Experimental Archaeology*, Coles (1979a: 101) states that "experiments have often been used to test stone axes, and sometimes iron and steel axes, but rarely bronze." His experimental work with bronze tools (flat axes, palstaves, and socketed axes) is alluded to elsewhere (Orme and Coles 1983: 21–22; Coles and Orme 1985: 25, 27, 30), but practically all of the specific experimental information can only be found in archived documents (Coles and Orme 1985: 30).

The published bronze axe research did not focus on tree felling, but rather on woodworking, whether of timber (Orme and Coles 1983) or roundwood (Coles and Orme 1985). The emphasis of the work was on gaining "an understanding of Somerset Levels species and the ways by which they might have been worked and therefore selected for various purposes" (Coles and Orme 1985: 36). They studied the type of marks or "signatures" various stone and bronze axes make (Coles 1979a: 103, 168; Orme and Coles 1983: 22–25; Coles and Orme 1985: 25–29), and compared the efficiency of woodworking with stone and metal axes (Coles 1979a: 168; Orme and Coles 1983: 25–43; Coles and Orme 1985: 30–36). The authors concluded that the introduction of bronze and iron blades basically did not change the technical ability of woodworking, though it may have affected the style of woodworking (Orme and Coles 1983: 43).

The need for a comparison of axe efficiency, including stone, steel, and particularly bronze axes, with respect to the felling of trees, controlling for as many variables as possible, having a large sample, and maintaining a natural tree felling environment, prompted us to design our own experiments.

The Experiment

Goals of the Study

The goals of our study were threefold. The primary goal was to compare the efficiency of bronze axes to steel axes, and then to compare these with stone axes. Recognizing that a number of variables could interfere with a straightforward comparison of these materials, our second goal involved investigating the effect that important variables have on tree-felling efficiency. These variables included tree type (hardness), haft length, blade width, axe weight, axe shape, and tree size. Many variables have been noted by previous researchers, but, as stated above, we wished to investigate these variables with larger samples and stricter controls. Finally, our third goal was to identify and discuss variables that have not received sufficient treatment in the literature.

Axes

The axes employed in our study were representative of three major technologies—steel, bronze, and stone, the latter subdivided into polished flint and ground stone.

Although specific ages are unknown, all of the steel axes used in the study were common commercially available types of the mid- to late-twentieth century. They were selected from the collections of two households in Vermont, where they remain in use to this day. These axes were hafted with commercially available wooden axe handles. From the range of forms available, we chose four axes on the basis of blade width, haft length, and weight.

The bronze axes were made specifically for this study. The process began with an examination of the small collection of bronze axes at the University Museum of Archaeology and Anthropology, University of Pennsylvania. We chose an axe that could be easily replicated by casting. The axe chosen was an unprovenienced "palstave" type belonging to the Middle Bronze Age of Europe (Tylecote 1986: 32–33), dated to between 1400–900 B.C. (Davey 1973: 52–53).

The next step was to identify a suitable chemical makeup for our replicas. We decided that a 90% copper, 10% tin bronze alloy was most appropriate because true tin bronzes contain 8–10% tin, 10% being considered the standard tin bronze (Tylecote 1986: 30, 1992: 20, 30). We then obtained 99% pure tin from a South Philadelphia recycling center and provided it to William Romanow, who prepared the alloy in the Materials Processing Central Facility of the Laboratory for Research on the Structure of Matter of the University of Pennsylvania.[1] Using 99.99% pure oxygen-free copper and the tin, Romanow produced the alloy. Any impurities remaining in the alloy were ignored because Bronze Age alloys also contained impurities.

Robert Engman of the University of Pennsylvania carved a wooden replica of the original artifact. This replica was then "rammed up in sand," which made a mould into which the bronze alloy was poured. Engman produced two bronze axes; he hammered one and the other was hammered by Mathieu.

Archaeologically these axe types have been shown to be hafted in a wood handle with a natural, L-shaped bend where the axe is attached that orients the axe head correctly. After inserting the axe head, the split is secured by some form of cord or rawhide wrapped around it. According to Coles, "wooden hafts for halberds and for bronze axes with flanges or sockets were made of bent pieces of wood (willow or oak), sometimes root, to provide the sharp angle for the axe attachment . . . " (Coles, Heal, and Orme 1978: 9).

We decided that to haft the axes in such a way would constitute an experimental archaeology study in itself. What was most important for our study was that the axe head be securely hafted. To do this, two ash pick-axe handles were cut to size, and openings were routered through the handles to fit the hafted ends of the axe heads. The axe heads, when fitted, protruded slightly through the back of the haft. After inserting the axe heads, wet rawhide was tied around the axe to add further support. This proved fruitless as the rawhide did not shrink and tighten upon drying, and thus played no part in securing the axe heads. Regardless, the hafting was secure (FIG. 1).

The stone axes used in our study are all Neolithic artifacts selected from the collections of the University Museum of Archaeology and Anthropology. The Artifact Destructive Testing Committee approved their use with the consent of the curator of the European Section. From the selection available we chose four axes: two of polished flint and two of ground stone (a third polished flint axe was later required as one of the original axes broke during felling). Of each material, we selected two sizes of axe, one relatively large and one relatively small, but each with roughly the same blade width (TABLE 1). Both of the ground stone axes are cataloged as Neolithic "stone implements" and described as ground axe-heads with flat edges from Lake Constance, Switzerland. These axes were made by pecking and grinding an aphanitic or granular, greenish, simatic stone. The flint axes, although more disparate in size than the ground stone axes, were similar in blade width. An origin in Scandinavia is the only provenience information available for the polished flint axes.

The stone axe heads were hafted in crude handles fashioned from either small saplings or tree branches (FIG. 2). All of the axe handles were made of ash leaf maple wood, which we found in some early trials to be more durable than the other available materials. We selected suitable trees or branches, cut them to appropriate lengths and stripped off their bark. After allowing them to dry, we

1. Mr. Romanow's work was supported by the National Science Foundation, MRL Program, under grant No. DMR88-19885.

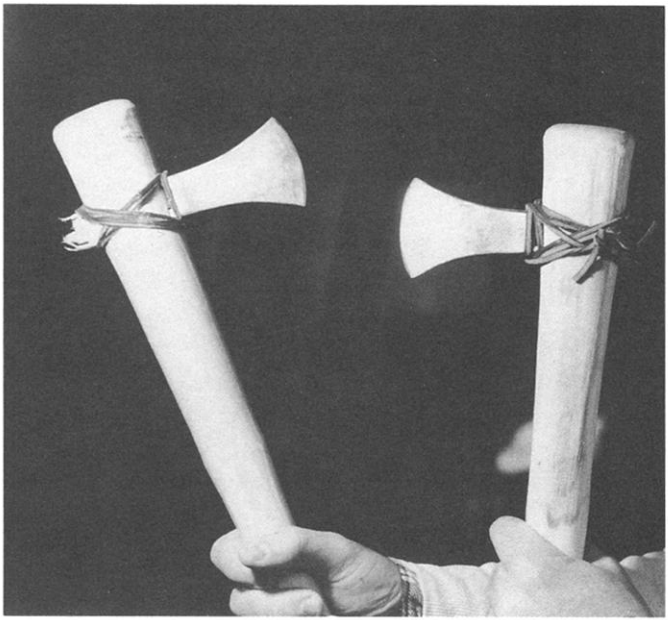

Figure 1. Hafted bronze axes used in the felling experiments. Photo D. Meyer.

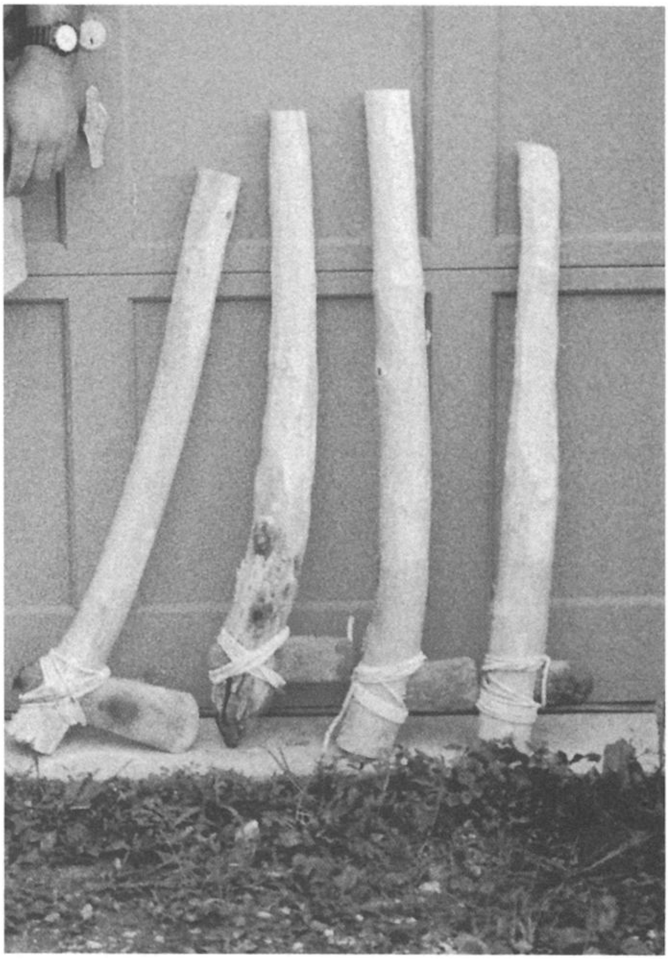

Figure 2. Hafted stone axes used in the experiments. From left to right: Stone 2, Stone 5, Stone 4, Stone 1. Photo J. Mathieu.

Table 1. Measurements of axes used in experiments. Axe weight includes both axe head and handle, as both affect the moment of inertia. For stone axes, the ID number followed by a decimal point indicates that the stone axe head had to be rehafted, hence the differences in axe weights and handle lengths.

Axes	*Weight (kg)*	*Blade width (cm)*	*Handle length (cm)*
Steel 1	0.6	5.5	30
Steel 2	0.76	9.0	36
Steel 3	1.55	9.3	69
Steel 4	2.37	12.0	91
Bronze 1	1.02	5.5	46
Bronze 2	0.96	6.0	47
Stone 1.1	1.03	5.3	77
Stone 1.2	1.91	5.3	72
Stone 2	1.68	7.6	73
Stone 3	1.89	8.0	73
Stone 4	1.78	6.6	80
Stone 5.1	2.02	5.3	76
Stone 5.2	2.19	5.3	74
Stone 5.3	3.37	5.3	72
Stone 5.4	3.17	5.3	71
Stone 5.5	2.75	5.3	76

chiseled an appropriate opening into the handle. Depending upon the thickness of the handle and length of the axe head, the axe head either went completely through the handle and protruded on the other side, or the hole went clear through but the axe head did not protrude through the rear of the haft.

The axe head was fitted into the hole so that the top and bottom (thin faces) of the axe head were held tightly in place, yet space was left between the sides of the shaft hole and the sides (broad faces) of the axe head. We did this based on a suggestion in Jørgensen (1985), whose experiments in Draved Wood showed that this technique would help keep the haft from breaking. The head was further secured into place by winding thin cotton rope around the outside of it. This was done mainly to keep the sides of the haft from popping out, as Jørgensen describes in his experiments, and also to prevent the axe head from popping out of the haft. Some of the handles fashioned in this manner did not withstand much chopping before they broke, whereas others lasted throughout the project.

Although the hafting was crude, we did not attempt to replicate Neolithic handles as did Jørgensen (1985) and Olausson (1983). We felt that although under optimum conditions Neolithic handles would have been best, Neolithic hafting was a skill we lacked. We decided that as long as the handles held the axe heads securely and they were comfortable to swing, the efficiency of the axe would not be affected.

The hafting of the stone axes was one of the least controlled aspects of this project. The range of variation covered by the axe weights and lengths (TABLE 1) is likely to be a source of uncontrolled error in the data. The length of the axe handles did not vary greatly, but the completed stone axes weighed anywhere from 1.03 kg to 3.37 kg. This variability of weight between axes would have been difficult to correct. Axe weight should be noted when considering all of the results from this project.

The steel and stone axes were sharpened with a foot-powered sandstone wheel, and the bronze axes were sharpened with sand paper. We did not measure the degree of sharpness obtained. The only axes resharpened during the trials were the stone axe heads, and only if their blades began to chip; resharpening was done to prevent them from shattering on further impact. Although the metal axes did dull somewhat, they remained sharp enough to efficiently fell the relatively soft temperate forest trees (cf. Carneiro 1979b, where much harder trees were felled).

Trees

The tree felling study began in the Spring of 1991 with the numbering and measuring of trees. Eligible trees of five different species were chosen from property in South Burlington, Vermont (TABLE 2). These trees were tagged and numbered, and their diameters (breast height) were measured with a diameter-ruled tape measure. An ideal selection of trees, i.e., four different hardwood and softwood species with equal numbers and ranges of diameter, was not available (the trees felled were part of a thinning project) and, as will be seen, the authors had to make do with what was available. The five tree types were poplar (*Populus deltoides*), white pine (*Pinus strobus*), ash leaf maple, also known as box elder (*Acer negundo*), sugar maple (*Acer saccharum*), and elm (*Ulmus americana*) (Desh 1981; Hawley and Wise 1926; Haygreen and Bowyer 1982; Summitt and Sliker 1974–1980; Wangaard 1981; USDA Forest Service 1974).

We chopped five hardwood trees and five softwood trees with each axe (for our purposes softwood refers to relatively softer trees and not necessarily conifers). We decided that all five hardwood or softwood trees should be the same species in order to control that variable. The result was that all steel and bronze axes felled five poplars (softwood) and five ash leaf maples (hardwoods). Unfortunately, we could not employ the stone axes on these two types of trees due to a lack of sufficient numbers of these species. Therefore, the steel axe data and the bronze axe data are easily comparable, whereas comparisons of the data for metal axes to the stone axe data are problematical. Because of the nature of previous experiments (which concentrated mainly on stone axes) we felt advantaging our bronze data was the best choice under the circumstances.

We assigned trees to each axe so that there would be an even range of diameters represented for each axe (TABLE 2). The final distribution of trees to axes was five poplars (soft) and five ash leaf maples (hard) to all metal axes, five white pines (soft) and five sugar maples (hard) to all polished flint axes, and five poplars (soft) and five elms (hard) to all ground stone axes.

Felling

Various techniques for felling trees have been described in the experimental literature. These include the use of a one-handed or a two-handed swing (Carneiro 1979a: 27; Morris 1939: 137); a full swing, utilizing the shoulders and upper torso, in contrast to a half swinging technique, "in which the blow is struck from the elbow, not the shoulder" (Harding and Young 1979: 104; Steensberg 1957: 68); "round cutting" the tree (Steensberg 1957:

Table 2. Nomenclature, specific gravities, and range of diameters of trees felled in the study.

Trees	*Specific gravity* *wet*	*dry**	*Size range felled (diameter in cm)*
Poplar *(Populus deltoides)*	0.37	0.40	8.00–40.06
White pine *(Pinus strobus)*	0.34	0.39	11.68–19.79
Ash-leaf maple *(Acer negundo)*	0.42	0.46	7.49–34.72
Sugar maple *(Acer saccarum)*	0.56	0.66	7.95–17.65
American elm *(Ulmus americana)*	0.44	0.54	8.76–17.07
European oak *(Quercus robur)*	–	0.72	–
European birch *(Betula pendula)*	–	0.67	–

* These data are available from a number of sources including Desh 1981; Hawley and Wise 1926; Haygreen and Bowyer 1982; Summitt and Sliker 1974–1980; Wangaard 1981, USDA Forest Service 1974. Oak and birch are not included in our study but are discussed in the text.

68) versus "cutting-to-fall" (Carneiro 1979a: 32; Jørgensen 1985: 31; Steensberg 1957: 68; Townsend 1969: 201); the use of double incisions on the same side of the tree that eventually converge into a single cut (Coles 1979a: 102); "girdling," "tree-ringing," "ring-barking," or stripping the bark off around the tree's circumference so that it will die (Carneiro 1974: 114, 1979b: 72; Coles 1973: 21; Coles, Heal, and Orme 1978: 28; Iversen 1956: 38; Jørgensen 1985: 39; Steensberg 1957: 68); burning the tree (Carneiro 1974: 114, 1979b: 72; Coles 1973: 21; Coles, Heal, and Orme 1978: 26; Shaw 1969: 52); and notching the tree to be felled by the wind or another falling tree (Steensberg 1980: 39; Carneiro 1974: 114–115, 1979a: 53–54, 1979b: 48, 54). Each of these methods has advantages, but we did not burn, notch, or girdle any trees, as it was the axes' efficiencies we wished to test. With respect to swinging and felling techniques, we employed whichever method seemed most useful for the situation, thereby assuming that maximization of effectiveness and minimization of time and effort was the norm.

Meyer, when employing Steel Axes 3 and 4, used a full two-handed swing. Mathieu, when employing Steel Axes 1 and 2, varied his stroke from one- to two-handed (this was possible due to the short haft). This variation avoided fatigue and allowed the best possible angles of approach on the trees. The flexibility of swings allowed by a short-hafted axe is an advantage when attempting to fell poorly positioned trees. The hafts of the bronze axes were not as long as Steel Axes 3 and 4, but were longer than Steel Axes 1 and 2. A two-handed swing was used by both experimenters with the bronze axes. The only variation was switching from a left- to a right-handed swing depending on the need to avoid obstacles of foot placement or to relieve stress on certain muscles. The stone axes all had long handles and were employed with both hands.

With the metal axes we employed the cut-to-fall technique, in which a second cut is made on the opposite side of the tree and slightly above the plane of the main cut. As the tree neared falling, small cuts were often made on the sides to crack the bark and outer rings. With the stone axes we generally used the cut-to-fall method, though on many trees a combination of cut-to-fall and round cutting was necessary. As a tree approached the point at which it was about to fall, the fellers attempted to push or pull the tree down. This is a tactic that would be employed by anyone desiring to fell a tree. Five trees needed to be cut completely through because their limbs were caught in other trees.

While the trees were cut, the observer timed the feller and counted the number of swings for each tree. After the trees were cut, the feller estimated the depth of the cut and the angle of the cut. The researchers recorded notes regarding damage to the axes such as flint chips or haft breakage, and other observations.

Results

Relative Efficiencies of Stone, Bronze, and Steel

Our scale of efficiency of an axe is dependent on the time required to fell a tree. We felled 20 trees (10 poplars and 10 ash leaf maples) with Bronze Axes 1 and 2 and 40 trees (20 poplars and 20 ash leaf maples) with Steel Axes 1, 2, 3, and 4. We graphed these two materials against each other in Figure 3. The graph fails to show any clear distinction between materials, and leads to the conclusion that bronze and steel axes are equally efficient for felling trees.

The efficiency of metal axes (both steel and bronze) versus stone axe efficiency is illustrated in Figure 4. This graph plots every tree felled with stone, bronze, and steel axes by axe material type. The graph shows that stone axes generally fell trees more slowly than metal axes. This result confirms the findings of earlier efficiency studies, but also allows further insight into the nature of felling trees with stone axes (see Meyer 1992).

Figure 5 also combines all trials and exhibits these distributions by blade material. Visual examination of the graph allowed us to judgmentally add two lines to Figure 5 to make certain distinctions clearer to the reader. These two lines divide the graph into four areas. Section A results from the use of stone axes only; it is the slowest region with respect to tree diameter. Section B shows the use of bronze, steel, and stone axes, and demonstrates that all axe types will fell a tree of small diameter relatively quickly. Other factors involved in tree felling, such as preparation time or walking to the site, may require more time than the actual tree felling. Section C shows that metal axes noticeably surpass the efficiency of stone axes on trees of large diameter. Section D should be a "no man's land," for as the tree diameter increases one would expect that the void between stone axe efficiency and metal axe efficiency would further separate (Carneiro 1979b; Mathieu 1992; Meyer 1992). This region is also the most likely to show unusual outliers, or tree types of unusually high or low specific gravities; either metal-axed trees that took an inordinately long time to fell, or stone-axed trees that fell unusually quickly.

From these graphs we conclude that the effectiveness within metals, i.e., between steel and bronze, is equal, and that the important difference in technologies lies between stones and metals.

The Effect of Metal Hardness on Efficiency

After using the metal axes and comparing their efficiencies, we removed samples from the blades of Bronze

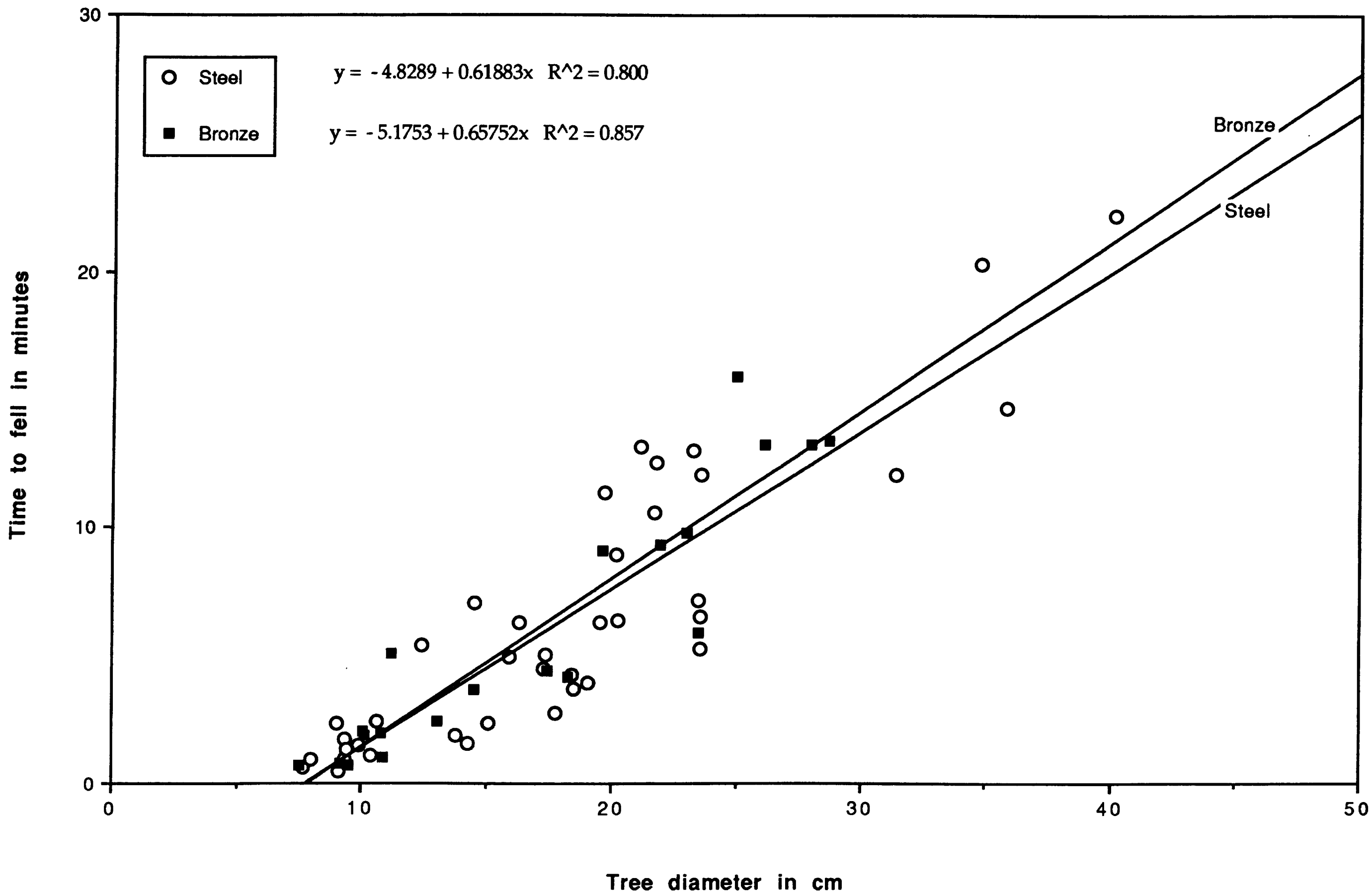

Figure 3. A comparison of all trees (regardless of species) felled with the steel axes and all trees felled with the bronze axes. Computer generated regression curves are linear.

Axes 1 and 2 and Steel Axe 2 and also one from an unworked bronze lug, in order to perform a hardness test of the blades. The hardness test made a dent in each of the samples and measured the hardness of the metals in vickers (HV). The hardness values for these samples were compared to the hardness of other metals. According to Tylecote (1986: 29), one would expect our 10% tin-bronze axes to have a hardness of 100 HV before hammering. Our unhammered bronze lug sample's value of 96 HV demonstrates a good match.

A 10% tin-bronze can be cold-worked to a hardness of 230 HV (Tylecote 1986: 29). Our two bronze axe samples produced hardnesses much softer than this, 108 and 144 HV (this difference is due to differential cold hammer-hardening). Our steel axe sample was harder, measuring 580 HV. If one were to use the metals' hardnesses to obtain "some idea of the mechanical properties and therefore of the value of an implement as a cutting tool" (Tylecote 1986: 32), one would suppose that the bronze axes would be inferior to the steel axes. Our study of tree felling does not support this idea. The bronze axes attained a level of hardness, with relatively little cold-working, sufficient to be used as a wood-cutting implement that was as efficient as steel. Bronze's softness does not allow the axe to hold an edge as long as steel, but the inability to hold a razor-sharp edge does not seem to affect the axe's efficiency. Although bronze requires more frequent sharpening than steel, its softness allows it to be sharpened more quickly.

If a 10% tin-bronze cold-worked to 108 HV is as efficient as a steel axe of 580 HV, as our study shows, then it can be suggested that other metals or alloys with comparable or higher hardnesses may also be equal in efficiency to steel axes when felling trees. For example, cold-worked, low-carbon wrought iron has a hardness which ranges between 150-250 HV (Buchwald and Leisner 1990: 100). Even air-cooled, unquenched steel[2] (con-

2. Steel is iron with a high, fairly homogeneous carbon content.

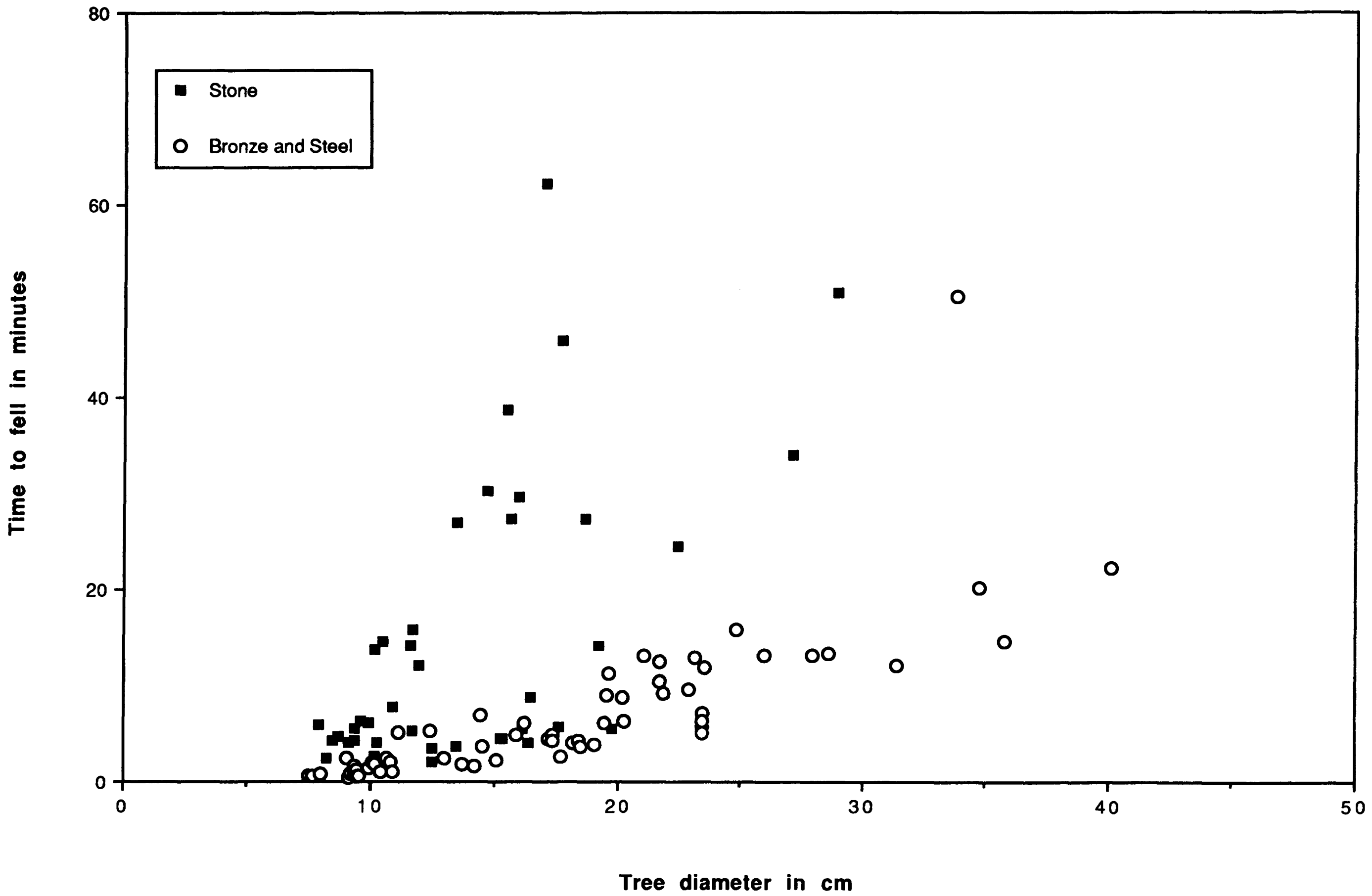

Figure 4. A comparison of trees felled with stone axes versus trees felled with metal axes (bronze and steel).

taining as much as 1% carbon) has a similar hardness, within the range of work-hardened tin-bronzes (Smith 1981: 94–95).

It would appear that from the time people used bronze to make axes, until quenching steel became common among blacksmiths to harden their steel,[3] the choice between metals to be used for axe manufacturing depended little upon their attainable hardness. This slight variation between metals makes arguments based on improved efficiency of one metal over another seem highly unfounded. Arguing that quenched steel axes improved efficiency is debatable, at least in regard to tree felling and other wood-working activities.

3. It is unclear when this actually happened, though it may not have been so even during Roman times in Europe (Vince Piggott, personal communication, 1993). Tylecote (1992: 53) states that ". . . the art of quench-hardening . . . was not widely practiced either in the Near East or in Europe during the pre-Roman Iron Age."

Efficiency and Tree Species

Our study confirmed the results of earlier experiments (and common sense) showing that harder trees generally require more time to fell than do softer trees. Figure 6 compares poplar and elm trees felled with stone axes in terms of time needed to fell with respect to tree diameter. Not surprisingly, the results show that the hardwood (elm) required more time to fell than the softwood (poplar). With metal axes this difference does not appear to be as large as with stone axes.

It has been posited elsewhere that the ratio of specific gravities of the tree types might be the relationship which best explains the difference in felling time (Carneiro 1979a: 51–53, 1979b: 60–63). Elm's specific gravity (0.44 wet, 0.54 dry) is greater than poplar's (0.37 wet, 0.40 dry).

The difference between the time it takes to fell softwoods compared to hardwoods is also clearly revealed in

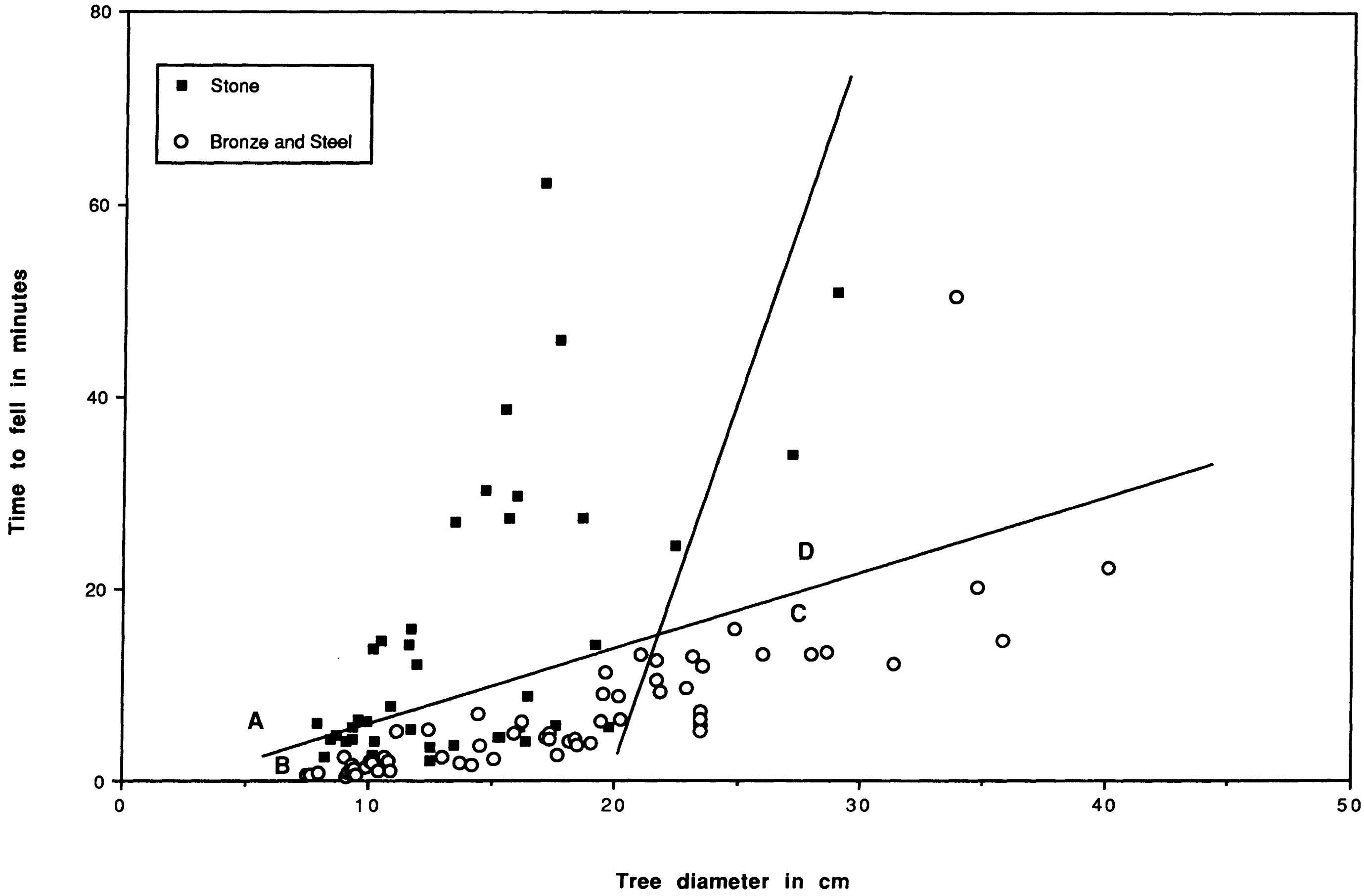

Figure 5. A comparison of trees felled with stone axes versus trees felled with metal axes (bronze and steel). The lines separating the graph into four sections were drawn by visual inspection. Section A represents the slowest felling times for relatively small trees, represented only by stone axes. Section B represents the size range in which any tree will be felled quickly with any type of axe. Section C represents the fastest felling times for relatively large trees, represented by metal axes only. Section D is a "no-man's land," where trees felled unusually quickly with stone axes or unusually slowly with metal axes are found.

Figure 7, which shows all of the trials using stone axes. The graph shows two major groupings, a larger one to the left and upper area and a smaller one to the right and lower area. All of the relatively soft trees, pine and poplar, with the exception of those felled by Stone Axe 1 (the least efficient of the stone axes), are in the right hand group, and all of the relatively hard trees, elm and sugar maple, are in the left hand group. Those softwoods felled by Stone Axe 1, though clustered in the left hand group (with the hardwoods), are the farthest to the right of that grouping. These data indicate that the softwood tree species require less time to fell than the hardwood tree species.

The above results confirm what common sense tells us about the differences between hardwoods and softwoods. Other tree characteristics, however, aside from specific gravity, will also affect the amount of time needed to fell a tree. An aspect of wood that is not readily quantifiable is how easily it is chopped, not in terms of hardness, but in terms of how "neat" the wood chips are. We noticed during chopping that pine, sugar maple, and especially ash-leaf maple produced large, cleanly-cut chips, whereas poplar and elm produced smaller chips that often looked "chewed" (not cleanly-cut, with a fibrous appearance). Jørgensen (1985: 48–49) also notes that other subjective, unquantifiable properties of wood affect felling. He describes oak as a firm wood that cuts and cleaves nicely. Maple is similar, but as the axe cuts into the heartwood of the tree, it becomes a difficult wood to chop. Even using a chainsaw, maple is one of the most difficult woods to cut through.

Figure 8 serves to illustrate this point. Sugar maple trees, with a specific gravity of 0.66 when dry, are plotted with European oak trees felled by Jørgensen, with a specific gravity of 0.72 when dry. European birch felled by Jørgen-

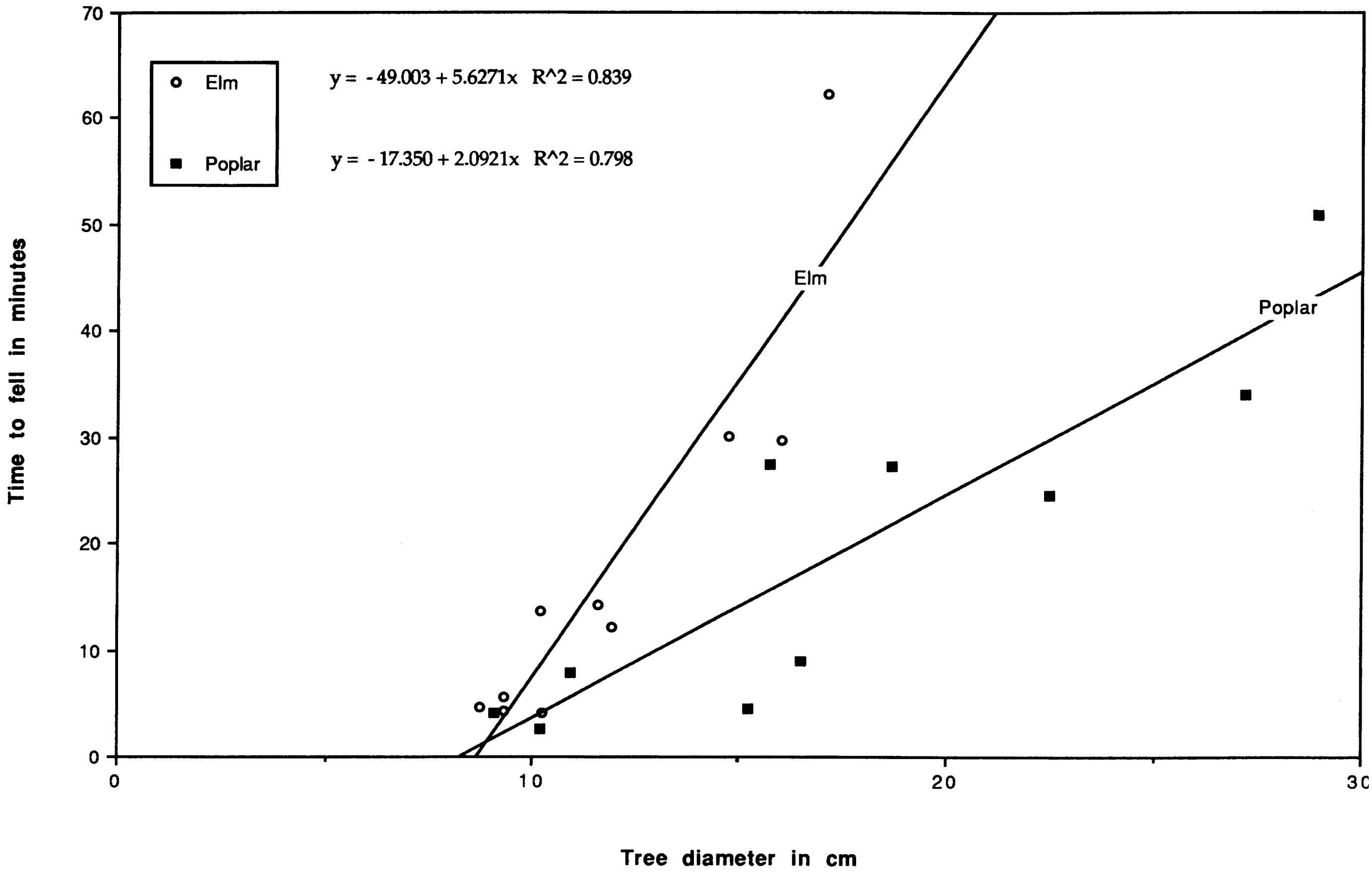

Figure 6. A comparison of poplar trees (*Populus deltoides*) and elm trees (*Ulmus americana*) felled with groundstone axes. The computer-fitted regression curves are linear.

sen, with a specific gravity of 0.67 when dry, are also plotted. Linear regression curves for each set of data were also plotted. Sugar maple trees, with the lowest specific gravity, took the longest time to fell, while oak and birch are in the order that one expects based upon their specific gravities. One may argue that Jørgensen's data are from a different set of experiments with a different set of fellers, and that this is the reason for the discrepancy between relative specific gravity and felling time for sugar maple trees. Our results, however, correspond well with Jørgensen's elsewhere (see Meyer 1992). This difference, unpredictable based on specific gravity alone, is more likely due to the fact that some types of trees, such as sugar maple and elm, are more difficult to chop down for reasons other than specific gravity or hardness.

Desh (1981: 176) notes two factors that modify the importance of specific gravity to the strength of the wood: the arrangement of individual plant cells, and the physicochemical composition of the cell walls. Both of these factors contribute to planes of weakness, and can cause the wood to either cleave relatively easily or cleave with greater difficulty, and produce the effects described above.

A final aspect of the differences between tree types noted in our study was the effectiveness of different types of stone axes on differing hardnesses of trees. Our impression, based on felling both hardwoods and softwoods with ground stone and polished flint axes, was that ground stone axes, which tended to be duller and thicker than flint axes, made it more difficult to penetrate the trees' wood, but the axe head was less likely to break than the flint axe heads. Conversely, the flint axes tended to have sharper, thinner edges which made it easier to penetrate the trees' wood, but increased the likelihood of the axe head breaking (as happened to one of our polished flint axes when it was employed on the hardwood sugar maple). These impressions may lead to the hypothesis of a geographically distributed dichotomy between polished flint and ground stone axes. The choice of material for axe manufacture may not only be linked to the availability of certain stone types, but also to the local flora. If the local flora is of a softwood

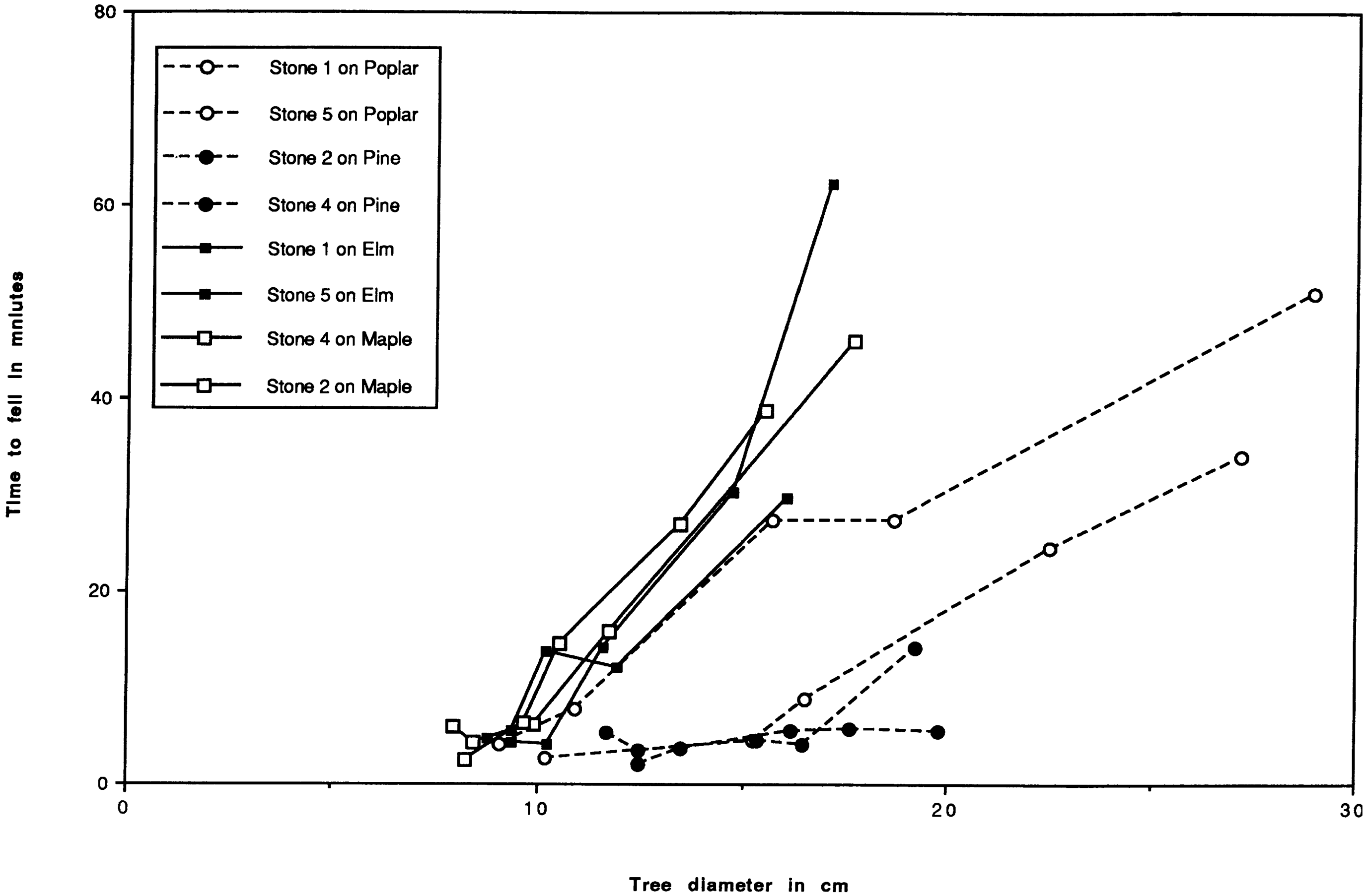

Figure 7. Graph plotting results of individual stone axes felling different tree species. The dashed lines represent relatively soft poplar (*Populus deltoides*) and pine (*Pinus strobus*) trees, and the solid lines represent relatively hard elm (*Ulmus americana*) and sugar maple trees (*Acer saccharum*).

nature, we may expect to find more polished flint axes, and conversely if the flora is normally hardwood, we may expect to find a higher proportion of ground stone axes.

Efficiency and Haft Length

Of the 60 trees felled with metal axes, 20 were felled with short-hafted steel axes (30 and 36 cm in length), 20 with medium-hafted bronze axes (46 and 47 cm long), and 20 with long-hafted steel axes (69 and 91 cm long). These three types of hafts were compared with one another to see which was most efficient in terms of felling time. We found that the efficiency of the long hafts becomes distinct only in trees exceeding 25 cm in diameter, when the increased length results in an increase in torque of the swing, and thereby an increase in power and moment of inertia of the axe head.

The rate of swing of different haft lengths was also recorded during the experiments. Not surprisingly, we found that short hafts are swung faster than medium hafts, which are swung faster than long hafts. By using 15 minutes (900 seconds) as a standard of comparison, generally a short haft was swung about 1000 times, a medium haft about 700 times, and a long haft about 450 times, which roughly equates to 1 swing per second for a short haft, 3 swings per 4 seconds for a medium haft, and 1 swing per 2 seconds for a long haft. It is interesting to note that the rate of swing of 1 stroke every 1.5 seconds noted by Carneiro (1979b: 47) for the Yanomamö falls within the range of variation observed in this study.

Efficiency, Blade Width, and Axe Weight

Blade width refers to the actual length of the cutting edge of the axe (not to the thickness of the implement). Steel Axes 2 and 3 have practically the same blade width, 9.0 and 9.3 cm respectively, and were compared with one another. It was observed that a discrepancy existed in favor of Steel 3 when felling trees greater than 25 cm in diameter. This discrepancy is believed to be due to the different

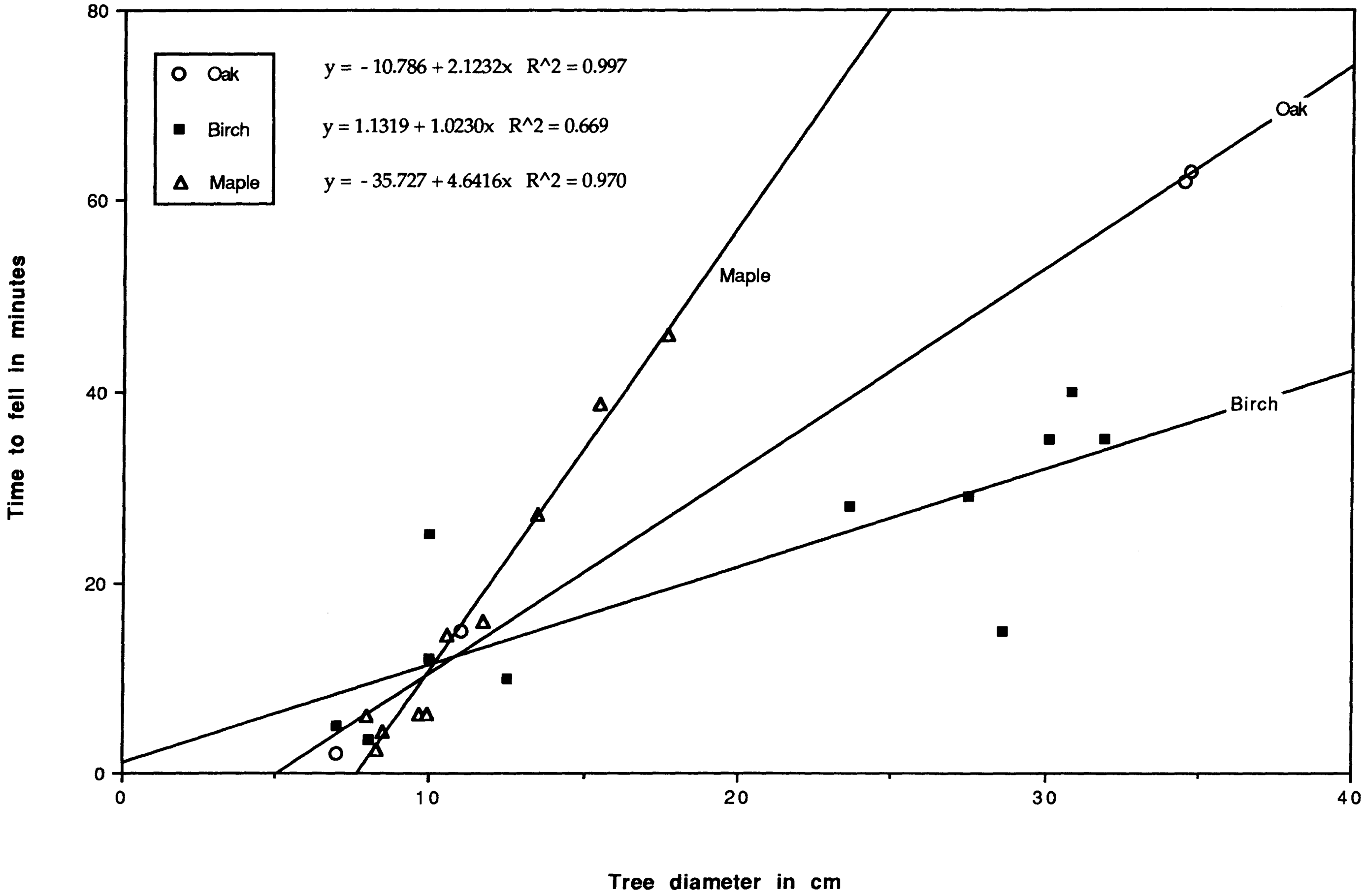

Figure 8. Graph plotting sugar maple trees (*Acer saccharum*) felled with flint axes, European oak trees (*Quercus robur, petraea*) felled by Jørgensen (1985) with flint, and European birch trees (*Betula pendula*) felled by Jørgensen (1985) with flint. The computer-fitted regression curves are linear.

haft size of the two axes. Steel Axe 2 had a haft length of 36 cm, whereas the haft of Steel Axe 3 was almost twice as long at 69 cm.

Figure 9 shows the results of plotting all trees felled with Steel Axes 1–4. The different blade widths' efficiencies are virtually indistinguishable up to 20 cm in diameter, except for Steel 1 which tends to be the least efficient. The width of its blade is 3.5–6.5 cm shorter than all the other axes, but the observed decrease in efficiency is far from proportional. After 20 cm in diameter, there is a slight difference between Steel Axes 3 and 4, which both have long hafts. Steel Axe 3 proved more efficient than Steel Axe 4 as tree diameter increases, which suggests that a smaller blade width (9.3 cm for Steel Axe 3) is more efficient than a longer one (12.0 cm for Steel Axe 4). We argue that this fact is more likely a result of axe weight rather than blade width. Steel Axe 4 was much heavier (2.37 kg) than Steel Axe 3 (1.55 kg), and thus slowed the rate of swing (see below). We conclude that blade width does not affect tree felling efficiency unless the blade width corresponds to an increase in axe weight, or the blade is simply too small to be effective (Steel 1 seems to be approaching this threshold). Blade widths of different length most likely correspond to the needs of maneuverability of axes employed for different uses, such as tree felling versus wood working.

We also wished to examine the effect of axe weight on efficiency in this study. Unfortunately, we were unable to directly control for this, so we must base our analysis on the assumption that blade width does not affect efficiency. We plotted the rates of swing of Steel Axes 3 and 4 versus time on poplar trees (FIG. 10). The graph shows that as time increases, the swing rate of Steel Axe 4 (the heavier of the two axes) falls away from Steel Axe 3. This is due to the greater fatigue felt by the feller with the heavier axe over time. This decrease in swing rate is arguably the reason behind the decrease in efficiency seen in the results of Steel Axe 4. The conclusion drawn here is that the swing rate of Steel Axe 4 slowed and its efficiency decreased compared

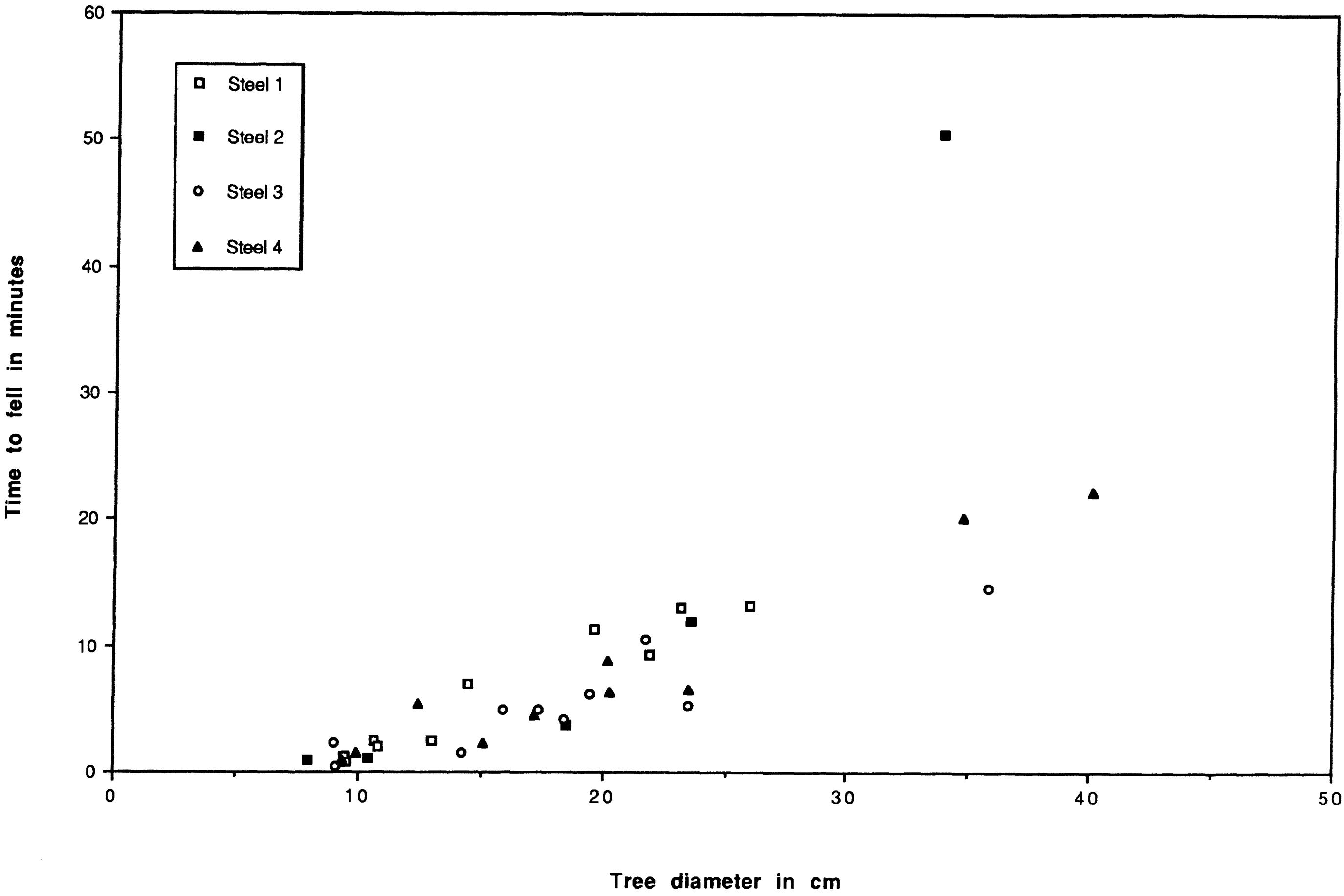

Figure 9. A comparison of axe blade width using all trees felled by individual steel axes. Steel 1 has an edge length of 5.5 cm, Steel 2 of 9.0 cm, Steel 3 of 9.3 cm, and Steel 4 of 12.0 cm.

to Steel Axe 3 as time increased, due to the greater weight of Steel Axe 4 and its effect on the feller's fatigue (which might not be an issue for a Neolithic tree feller used to such labor). No general conclusions regarding axe weight can be made, as the effects of axe weight on efficiency will vary considerably with axe type, the use to which the axe is put, and individual fellers.

Efficiency and Axe Shape

It was believed that the only way in which the axe shape would affect the felling of a tree was in terms of the axes' ability to penetrate the wood of the tree. Logically, a thinner axe shape should be advantageous in penetrating a tree. Because metal axes are much thinner than stone axes, a comparison between metal and stone axe penetrability seemed most appropriate. We decided to approach the issue by observing the angle of cut of the felled trees as a measure of how wide an opening in the tree was necessary for the axe to penetrate the deepest parts of the tree, and therefore to fell it. It was found that the angle of cut for all metal axes ranged from 40–90 degrees, averaging 70 degrees, with a standard deviation of 13 degrees. In contrast, the angle of cut for all stone axes ranged from 60–110 degrees, and averaged 85 degrees, with a standard deviation of 12 degrees. A one-tailed t-test run on these data produced a probability of less than 0.0005, demonstrating a significant difference in the angle of cut for the two axe types. The metal axes were more efficient at penetrating the heartwood because they required a smaller entry into the tree, with the result that less wood needed to be removed from the tree in order to fell it.

This improved penetrability of metal axes plays a part in the detaching of a felled tree from its stump. We noticed that a tree was more easily detached from its stump with a metal axe than with a stone axe.

Dickson (1981: 92) made an interesting observation about the use of steel over stone axes in Australia:

> What pleased the [Australian] Aborigines about steel hatchets [overstone axes] was not that a task could be done more quickly but that it was so much easier . . . It is the fine blade

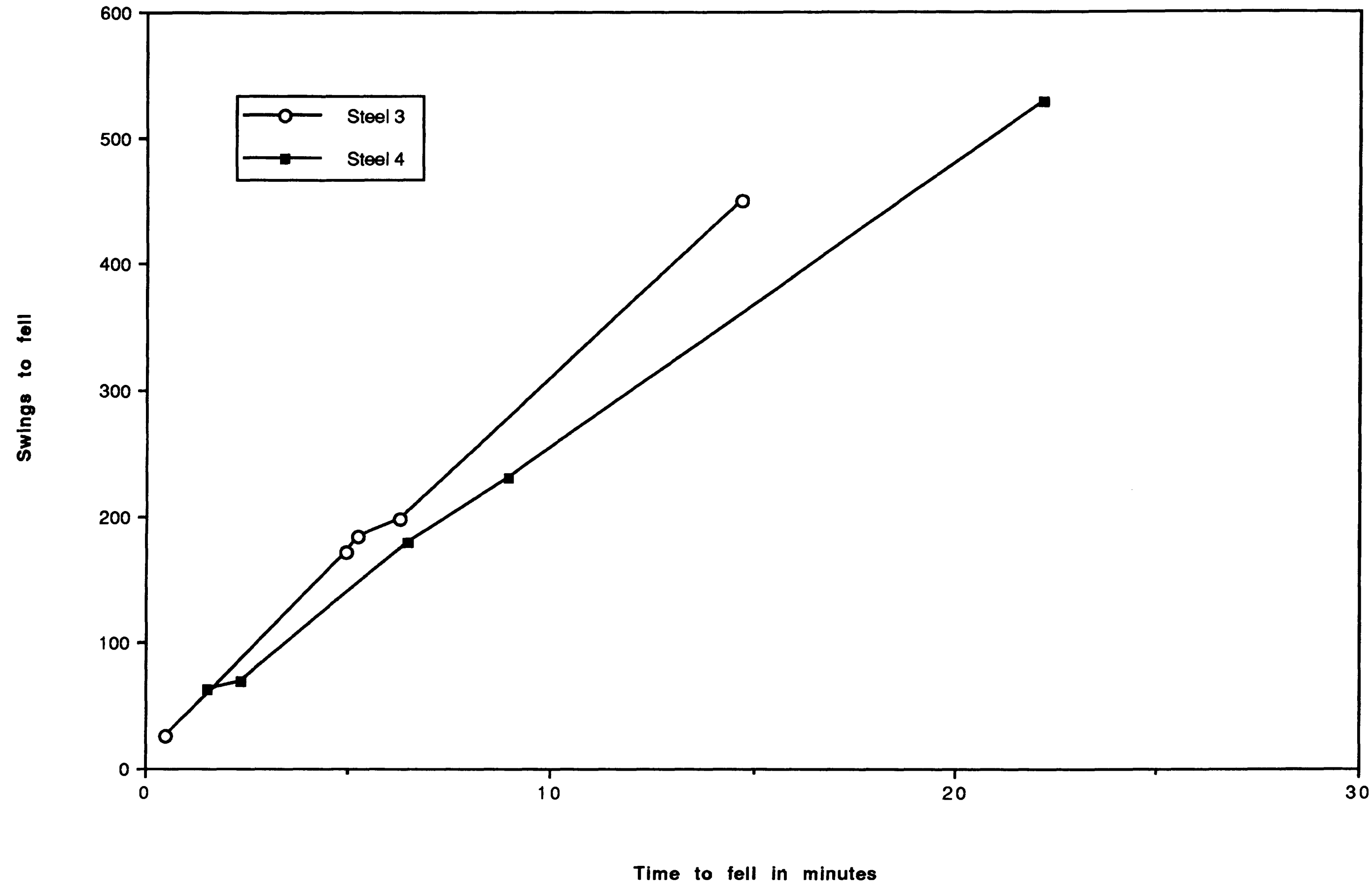

Figure 10. A comparison of swing rate over time with axes of different weight. The data plotted are Steel 3 (1.55 kg) versus Steel 4 (2.37 kg) felling poplar trees (*Populus deltoides*).

which can be used at a low angle of attack that gives the steel hatchet its advantage . . .

Metal axes can shave trees more easily, get into tighter places, be aimed more accurately, allow easier preliminary shaping of wooden objects, and quicken the process of detaching felled trees from stumps. This further illustrates that it is not only the sharpness of steel that gives it an advantage, but also its thin shape makes its use easier.

Efficiency and Tree Size

Analysis of the data from this study led to an interesting insight. All the graphs that plot "time to fell in minutes" against "tree diameter in cm" show a distinct convergence of the data around the 10 cm diameter mark. The clumping of results at and below this diameter suggests that small trees can be easily felled by any axe type and that the important variables may not be ones we controlled for in this study, but factors such as vegetation and topography which make up the "felling environment" and which are difficult to control in experimental situations. Once a tree's diameter reaches about 20 cm, the tree's species and size seem to play a larger role in the amount of time necessary to fell. Trees under 10 cm in diameter will be felled quickly with any type of axe, and other factors such as walking out to the felling site and clearing vegetation probably contribute greater time costs to a project than the actual felling.

Variables

Table 3 lists the variables affecting tree felling previously noted in the literature, and whether or not we attempted to control for them in our trials. In the course of our study, we noted other relevant variables, which we felt were significant enough to merit discussion. The most important of these is what we call "the felling environment" (Carneiro 1979b: 40–42 discusses similar problems, but treats most of them as part of the field-clearing process). Felling environment involves a number of factors that, in combination or alone, can affect the time to fell a tree. For example, the lean of a tree can increase the speed of felling

Table 3. Previously noted variables affecting tree felling.

Variable	*Previous mention*	*Control in our study*
Access to tree	Jørgensen 1985: 49; Carneiro 1974: 114; Townsend 1969: 201	Only discussed
Age of tree	Harding and Young 1974: 104	Not accounted for
Diameter of tree	Most previous studies	Controlled for
Dryness of wood	Jørgensen 1985: 48; Orme and Coles 1983: 21	Not accounted for
Hardness of wood	Carneiro 1974: 114, 1979a: 51–52, 1979b: 60–65; Harding and Young 1979: 104; Olausson 1982: 31; Townsend 1969: 201	Controlled for
Small trees rebound from axe	Townsend 1969: 203	Not accounted for
Soft wood catching axe	Steensberg 1980: 25, 36	Not accounted for
Axe material	Carneiro 1974: 203, 1979b; Dickson 1981: 92; Godelier and Garanger 1973: 210; Olausson 1982: 32; Saraydar and Shimada 1971, 1973; Steensberg 1980; Townsend 1969: 201	Controlled for
Axe weight	Carneiro 1979a: 49; Olausson 1982: 33	Only discussed
Blade shape	Bordaz 1970: 99; Carneiro 1979a: 49; Clark 1945: 68; Coles 1979a: 102; Dickson 1981: 92; Olausson 1982: 33; Semenov 1964: 130	Only discussed
Blade sharpness	Coles 1979a: 102	Only discussed
Hafting	Carneiro 1979a: 49; Olausson 1982: 33; Orme and Coles 1983: 21	Controlled for
Broken axes	Jørgensen 1985: 49; Townsend 1969: 201	Only discussed
Condition of fellers	Carneiro 1974: 114; Coles 1979a: 102; Harding and Young 1979: 103; Jørgensen 1985: 49; Olausson 1984: 40; Orme and Coles 1983: 21; Townsend 1969: 201	Only discussed
Injury to fellers	Jørgensen 1985: 49	Not accounted for
Luck	Jørgensen 1985: 49	Not accounted for
Technique of felling	Carneiro 1979b: 45–57; Jørgensen 1985: 49; Olausson 1982: 40	Only discussed
Weather/season	Jørgensen 1985: 49; Olausson 1982: 39; Orme and Coles 1983: 21	Not accounted for

by allowing gravity to contribute to the trunk snapping off or, conversely, it can increase the time to fell by requiring extra chopping to get the tree to fall in the "right" direction. The local topography (slope, gullies, etc.) around a tree can increase felling time by interfering with the feller's footing. The vegetation around a tree can increase felling time by making approach to it difficult or requiring extra time for its removal before felling commences. Also, flying insects can create delays in the felling of a tree if their annoyance is particularly persistent and unpleasant. Carneiro (1979b: 41) observed a similar problem with ants in the Venezuelan rainforest.

Another factor is the purpose of the tree felling, and the length of time in which the project must be completed. If it is not crucial that a tree fall immediately, perhaps when clearing fields in the off-season, then a short period of chopping may suffice to make the tree vulnerable to other forces such as wind, gravity, insects, and decomposition which will eventually drop the tree. In contrast, if there is a pressing need to fell a tree quickly, certain techniques may be chosen over others, for example, burning or pulling a tree down rather than continuing to chop. This pressing need may also contribute to the increased incidence of an emotional variable in the felling process; frustration and anger over difficulties may increase or decrease the time required to fell.

These variables may come into play in any situation where a tree is to be felled. The large variances seen on a number of the graphs printed here (FIGS. 3–6) illustrate this point. Although we noticed the existence of these variables during our experiments, we do not believe that they adversely affected our results and the conclusions drawn from them. They should, however, serve as reminders that felling a tree or clearing land involves more than an axe, some trees, and a human being.

Conclusions

This study has led to several important conclusions concerning tree felling with stone, bronze, and steel axes. Of foremost interest is that bronze axes are as efficient as steel axes for felling trees. The hardness of the metal is not as important in felling a tree as one might suspect because only a minimum hardness is necessary. Bronze and steel axes can be considered under one efficiency category, metal axes, and as a material type are more efficient at felling trees than are stone axes, especially as tree diameter increases. This is due, in large part, to the thickness of the stone axes relative to metal axes, not necessarily only due to the superior sharpness of the cutting edge of the metal axes. The thickness of stone axes decreases the penetrability of the axe and increases the amount of wood that needs to be removed in order to fell the tree.

We also confirmed a number of factors that affect the rate of tree felling. The two most important are tree type (hardness and composition) and tree size, and future studies of these variables will likely provide the best estimates of time to fell a tree. With respect to tree type, one caveat from our study should be noted. Although specific gravity is the most important property in determining a tree's hardness (and therefore time to fell), it is not the only property that has such an effect. The arrangement of plant cells in different types of wood and the physico-chemical composition of the cell walls both contribute to planes of weakness and to felling time. Therefore, although specific gravity can be used as a rough measure of relative time to fell, as we saw in the example of oak versus sugar maple, this relationship is not absolute.

Handle or haft length is also an important factor in determining an axe's efficiency. A long-hafted axe will swing at a slower rate than a short-hafted axe, but will have greater efficiency over time on larger trees. On small trees there is little difference, but on larger trees the greater power afforded by a long haft will significantly affect the outcome.

The axe's blade width was found not to affect significantly the efficiency of an axe when felling a tree unless it also entailed an unusual increase in axe weight, which could affect the swing rate over time, and thus the efficiency of the axe.

A person can quickly fell a tree with a diameter of less than 10 cm, regardless of the type of axe used. In such situations, it is likely that several unquantifiable factors, such as the "felling environment" (vegetation, topography, insects) or preparation time will increase the amount of time involved. These factors can override the normally more important aspects such as tree type and diameter. But once the tree to be felled reaches a diameter of 20 cm or greater, these unquantifiable effects become less of a factor, and progressively become filtered out.

Finally, a conclusion about the use of experimental estimates to determine construction times in prehistory should be made. Especially with the use of stone axes, one should not necessarily rely on works such as this one, or Carneiro's (1979a, 1979b), Jørgensen's (1985), or Townsend's (1969) for reliable estimates (Meyer 1992). Because certain aspects such as tool type (e.g., groundstone versus flint), tree species, and environmental factors can have a profound effect, regionally specific estimates are in order. That is, unless significant research in one's area and environment using specific tool types has been carried out, an interested party needs to complete such experiments to provide the most useful estimates of time to fell a tree.

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