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## Origins of Agriculture in Eastern North America

BRUCE D. SMITH

As a result of research carried out over the past decade, eastern North America now provides one of the most detailed records of the origins of agriculture available. Spanning a full three millennia, the transition from forager to farmer in eastern North America involved the domestication of four North American seed plants during the second millennium B.C., the initial emergence of food production economies based on local crop plants between 250 B.C. and A.D. 200, and the rapid and broad-scale shift to maize-centered agriculture during the three centuries from A.D. 800 to 1100.

THE DEVELOPMENT OF AGRICULTURE HAS LONG BEEN CONSIDERED a major milestone in human evolution. During the past 10,000 years agricultural economies have also caused significant changes in the earth's ecosystems. This post-Pleistocene transition from foragers to farmers, from a reliance on wild species of plants and animals to food production economies, took place at different rates and times in various regions of the world and involved a rich variety of crop plants (1). In many regions this developmental transition with its major consequence for human societies and terrestrial ecosystems is far from well documented. As a result of a substantial increase in the amount, quality, and variety of information gained for eastern North America during the past 10 years (2, 3), this region now provides one of the most detailed records of agricultural origins available.

The recent increase of essential information on agriculture in eastern North America is in large part attributable to the application of four important technological advances to archeology and serves to underscore the important role of instrumentation in guiding and stimulating research (4). (i) Water flotation technology has produced dramatic improvements in the recovery of small carbonized seeds and other plant parts from archeological contexts (5); this technology has allowed the development of detailed temporally long archeobotanical sequences for different areas of eastern North America [see, for example, (6–9)]. (ii) Scanning electron microscopy (SEM) has documented minute morphological changes in seed structure associated with the process of domestication (10). (iii) Accelerator mass spectrometer (AMS) radiocarbon dating has provided, for the first time, accurate and direct age determinations of very small samples of seeds and other plant parts (11, 12). (iv) Stable

carbon isotope analysis of human bone (13, 14) has been a direct means of observing temporal and geographical trends in the relative consumption of maize by prehistoric groups in eastern North America.

As might be expected, recent advances in the recovery, identification and quantification, and accurate temporal placement of domesticated plant species in eastern North America have shown that the transformation of forager to farmer was a longer and more complex process than previously thought. In general treatments of the topic, for example, three aspects of the agricultural transition—plant domestication, the development of food-producing economies, and the shift to monocrop systems—are often either singled out or causally and temporally conflated as marking the origin of agriculture. In the archeological record of eastern North America, however, these three shifts can be clearly recognized as distinct episodes of change that are linked developmentally yet separated temporally, forming a sequence that spans three millennia.

Between 2000 and 1000 B.C. native North American crop plant species were initially brought under domestication in eastern North America, as indicated by distinctive morphological changes in the structure of reproductive propagules (fruits and seeds) associated with the adaptive syndrome of domestication (15).

Seven to 12 centuries later, between 250 B.C. and A.D. 200, a subsequent initial emergence of food production economies took place, with local crop plants gaining considerable economic importance. This is reflected in increased representation in seed assemblages, as well as by other related developments in technology and settlement patterns, for example (16, 17).

Six to nine centuries later, between A.D. 800 and 1100, a shift in food production economies occurred and a single nonindigenous species (maize) came to dominate the fields and diets of farming societies. This shift is reflected in an increased representation of maize in archeobotanical assemblages. More directly, changing  $\delta^{13}\text{C}$  ratios in human bone indicate an increased consumption of a C-4 plant (maize) relative to the intake of indigenous wild and cultivated C-3 food plants (13, 14).

### An Independent Center of Plant Domestication

In 1971, Harlan outlined three localized centers of plant domestication (the Near East, north China, and Mesoamerica), along with three larger, dispersed noncentral areas of domestication (Africa, southeast Asia, South America) (18). Although the status of eastern North America was far from clear at that time, it can now be identified as a fourth independent and localized center of plant domestication (Fig. 1) (15).

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As recently as 1985, however, the established presence during the Middle Holocene (6000 to 2000 B.C.) of a small, thin-walled (<2.0 mm) gourd in the region appeared to have confirmed eastern North America as a secondary recipient of domesticated plants and agricultural concepts from Mesoamerica. In the 1980s, a series of direct AMS radiocarbon dates were reported for rind fragments of a variety of small, thin-walled gourd assignable to the genus *Cucurbita* that had been recovered from five sites: Koster (two dates, 5150 and 4870 B.C.) (9), Napoleon Hollow (5050 B.C.) (9), Carlston Annis (3780 B.C.) (19), Bowles (2110 B.C.) (19), and Hayes (4390 B.C.) (20). A direct AMS date has also been obtained on a *Cucurbita* seed from Cloudsplitter (2750 B.C.) (21). In addition, 65 measurable *Cucurbita* seeds and ten rind fragments were recovered from well-dated contexts at the Phillips Spring site (2300 B.C.) (Fig. 1) (22).

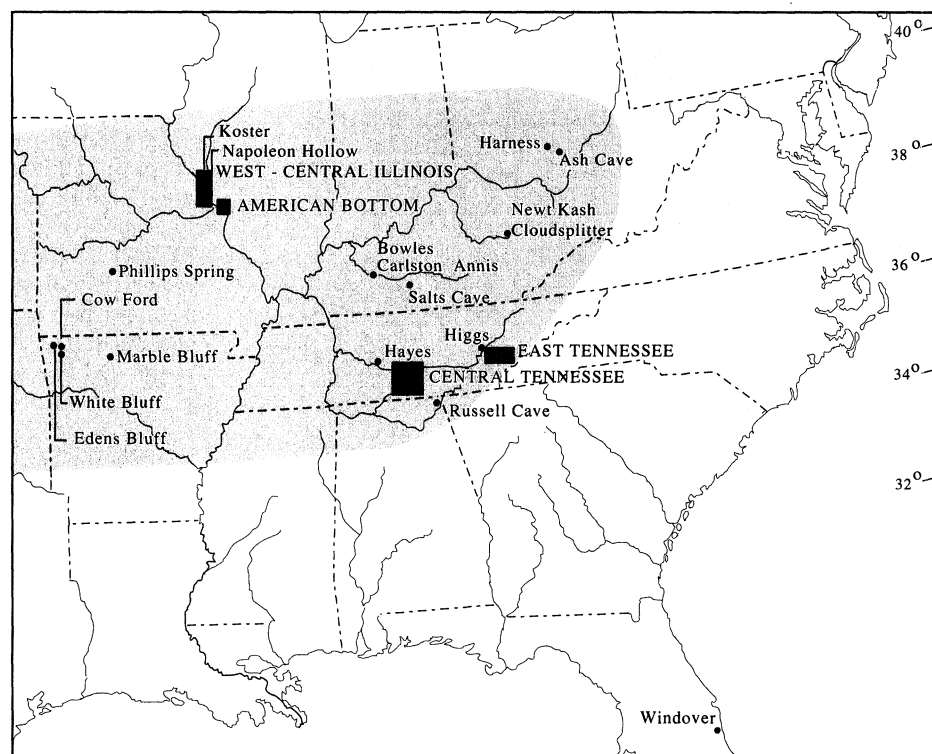
In the apparent absence of any modern species of wild *Cucurbita* gourd north of Texas, these firmly dated rind fragments and seeds appeared to demonstrate that the tropical domesticate *Cucurbita pepo* had been introduced into the region from Mesoamerica, along with the concept of agriculture, long before the 2000 to 1000 B.C. period of initial domestication of North American plants in the region. Alternatively, it was suggested that these early rind fragments and seeds reflected a more widespread Middle Holocene geographical distribution of an indigenous small, thin-walled gourd (compare *C. texana*) (21, 23). Morphological analysis of the available archeological specimens (15, 23) and recent taxonomic research on *Cucurbita* by Decker (24, 25) now strongly support the latter explanation. None of the rind fragments or seeds of *Cucurbita* gourd recovered from contexts before 2000 B.C. in eastern North America can be identified morphologically as representing a domesticated form of *C. pepo*.

On the basis of rind and seed measurements and morphology, specimens recovered from Cloudsplitter (about 850 to 350 B.C.) and Salts Cave (about 550 B.C.) (Fig. 1) provide the earliest evidence of large, thick-walled, clearly domesticated varieties of *C. pepo* in eastern North America (15, 22, 26, 27). These thick-walled domesticated varieties of cucurbit may have been introduced from

Mesoamerica at about 1000 B.C. It appears more likely, however, that they were initially domesticated in eastern North America during the period 2000 to 1000 B.C. from the indigenous *C. texana*-like wild progenitor discussed above. Decker (24) has recognized a taxonomic dichotomy of *Cucurbita* at the subspecies level that supports the idea of two independent centers of domestication for the species. Pumpkins, marrows, and a few ornamental gourds of one subspecies (*C. pepo* ssp. *pepo*) appear to have been first domesticated in Mesoamerica, with acorn squashes, scallop squashes, fardhooks, crooknecks, and most of the ornamental gourds of the second subspecies (*C. pepo* ssp. *ovifera*) having been domesticated in eastern North America. Thus, rather than relegating the region to a role of secondary recipient of agriculture from Mesoamerica, *Cucurbita* taxonomy and the archeological record underscore the identity of eastern North America as an independent center of plant domestication.

Similarly, two reports from Middle Holocene contexts of another potentially introduced domesticate, the bottle gourd (*Lagenaria siceraria*), do not cast doubt on the evidence for eastern North America as an independent center of plant domestication. Wild forms of the bottle gourd have never been located or described. As a result, morphological differences between wild and domesticated varieties have yet to be documented (23, 28). The Phillips Spring (2300 B.C.) (22) bottle gourd rind fragments and seeds are among the smallest known for the species and cannot be assumed to represent an introduced domesticate (23). The small, fragmentary, thin-walled bottle gourds recovered from the Windover site (5350 B.C.) (29) on the east coast of Florida (Fig. 1) are similarly dubious as domesticates. They do serve, however, to underscore the possibility that undomesticated bottle gourds were first carried to eastern North America by ocean currents, either from Africa or tropical America, at an early date (15, 23, 29).

In addition to the likely domestication of squash (*C. pepo* ssp. *ovifera*), three other native North American plants were brought under domestication in eastern North America during the second millennium B.C.: sumpweed or marshelder (*Iva annua*), sunflower

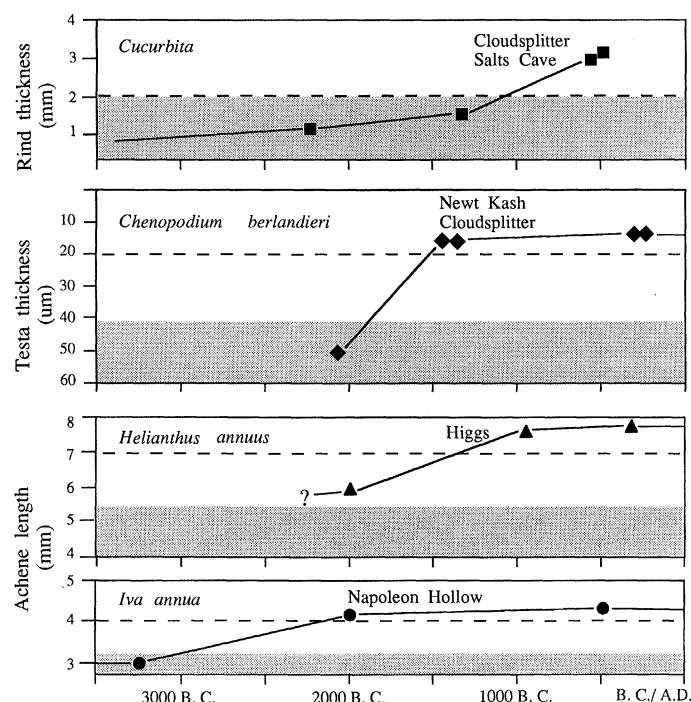


**Fig. 1.** Archeological sites and regions that provide information on agricultural origins in eastern North America. Shaded area indicates the interior mid-latitude zone of domestication of native North American seed crops at 2000 to 1000 B.C. and initial development of early food production economies at 250 B.C. to A.D. 200.

(*Helianthus annuus*) (30), and chenopod (*Chenopodium berlandieri*). For marshelder and sunflower, the morphological change indicating domestication is an increase in achene size (9, 31), whereas a reduction in seed coat (testa) thickness reflects the transition to domesticated status in *Chenopodium* (12, 15, 32).

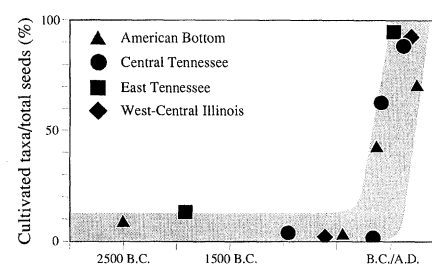
The temporal trends of increase in the size of marshelder and sunflower achenes in eastern North America are shown in Fig. 2. With a mean achene length of 4.2 mm (a 31% increase over modern undomesticated *Iva* populations), the approximately 2000 B.C. Napoleon Hollow *Iva* assemblage marks the earliest evidence for domestication of marshelder in the region (9). Similarly, the approximately 900 B.C. Higgs site sunflower achenes, with a mean length of 7.8 (as opposed to modern wild populations, which range in mean length from 4.0 to 5.5 mm), provide the earliest evidence for domestication of this species in eastern North America. Representing an early but not initial stage of domestication (31), the Higgs sunflower achenes suggest that initial domestication of *H. annuus* occurred at about 1500 B.C. (Fig. 2) (31, 33, 34).

This proposed initial domestication of *H. annuus* at about 1500 B.C. corresponds to the earliest evidence for the presence of a thin-testa domesticated form of chenopod (*C. berlandieri* ssp. *jonesianum*) (35) in eastern North America. Whereas modern wild populations of *C. berlandieri* in eastern North America have testa thickness values of 40 to 80  $\mu$ m (36), chenopod assemblages with thin testas (<20  $\mu$ m) have been reported from a number of sites dating from 980 B.C. to A.D. 150 (Ash Cave, Edens Bluff, Marble Bluff, Russell Cave, and White Bluff) (12, 15). Direct AMS dates on thin-testa chenopod specimens from Newt Kash (1450 B.C.) and Cloudsplitter (1500 B.C.) provide the earliest evidence for domestication of this species in the region (37). A second type of cultigen *Chenopodium* having an extremely thin, translucent seed coat has been documented at the Cow Ford site by A.D. 330 (Fig. 1) (12), and specimens recovered from about 700 B.C. contexts at Cloudsplitter suggest that it too



**Fig. 2.** The second millennium B.C. domestication of indigenous crop plants in eastern North America based on morphological changes in reproductive propagules. Adapted from (15). Shaded area, modern undomesticated size range; ----, baseline for domestication.

**Fig. 3.** The initial emergence of food-producing economies in eastern North America, as reflected by increased representation of cultivated taxa in four regional archeobotanical sequences (16).



may have been brought under domestication during the second millennium B.C. (38).

Both of these second millennium B.C. morphological changes are the result of strong selective pressures within seed beds favoring seedlings that germinate quickly (reduced testa thickness and germination dormancy), and grow rapidly (increased seed size and food reserves) (32, 39). As such, they provide clear evidence of a major second millennium B.C. escalation in the level of human intervention in the life cycle of these crop plants—the deliberate storage and planting of seed stock. This major step of planting was preceded by a three-millennium-long (about 5000 to 2000 B.C.) co-evolutionary process, with human and plant populations interacting within river valley settings across a broad interior riverine area of eastern North America (Fig. 1).

In some segments of mid-latitude (34° to 40° N) river valleys, the widely scattered short-term occupations by antecedent forager bands were replaced, in the period 5000 to 2000 B.C., by deep shell and midden-mound settlements (15, 17). These midden mounds and shell mounds were often located close to oxbow lakes and shoal areas having abundant aquatic resources, as humans narrowed their site preference and responded opportunistically to Middle Holocene river valley stabilization and biotic enrichment. Apparently reoccupied annually through the growing season, such settlements constituted the initial emergence of continually disturbed anthropogenic habitats in eastern North America. Within such habitats, a wide range of human activities would have frequently disturbed and enriched the soil, providing excellent long-term colonizing opportunities (15, 40) for a variety of early successional floodplain plant species, including *C. berlandieri*, *I. annua*, *H. annuus* (30), and *Cucurbita* gourd.

It is within such disturbed “domestilocality” (15) settings that the long, gradual developmental pathway to plant domestication likely took place. Initially neither requiring nor receiving any human assistance other than inadvertent soil disturbance and enrichment, colonizing weedy stands of these four species, through simple toleration, provided a localized and predictable supplement to “natural” floodplain stands. Although the archeological record does not show the stages, a gradual co-evolutionary progression of increasing human intervention would have gone from initial toleration through first inadvertent and then active, intentional encouragement of these food plants to the deliberate storage and planting of seed stock (15, 32). It is this critical and deliberate step of planting that marks the beginning of cultivation and the onset of automatic selection pressures within affected plant populations that produce the morphological changes associated with domestication (39). This co-evolutionary progression, which occurred over a span of two to three millennia, transformed stands of colonizing weeds first into inadvertent or incidental gardens and finally, by the second millennium B.C., to intentionally managed and maintained gardens of domesticated crop plants.

Within the annual economic cycle of incipient agricultural groups in eastern North America, these initial domestilocality gardens likely played a significant role in providing a dependable, managed, and

storable food supply for late winter to early spring (19, 21, 41). From the limited occurrence of seeds of these species in archeobotanical assemblages before 500 B.C., however, domesticated crops did not become a substantial food source, and food production did not play a major economic role until 500 B.C. to A.D. 200, a full thousand years after initial domestication.

## The Emergence of Food Production Economies

The period from 250 B.C. to A.D. 200 witnessed the initial development, subsequent elaboration, and eventual cultural transformation of the Middle Woodland period Hopewellian societies of eastern North America. The large and impressive geometric earthworks, conical burial mounds, and elaborate mortuary programs of Hopewellian populations have been the focus of archeological attention for well over a hundred years (42). It is only within the past decade, however, that much information has been recovered concerning Hopewellian food-producing economies.

For almost 30 years discussions of Hopewellian domesticates centered almost exclusively on the dietary role of maize (*Zea mays*), which had been recovered from contexts that suggested an arrival in eastern North America as early as 500 B.C. Recent direct AMS radiocarbon dates on proposed early corn, however, have substantially revised the timetable of initial introduction. The earliest convincing macrobotanical evidence of the presence of maize in eastern North America is the directly dated carbonized kernel fragments from the Icehouse Bottom site (A.D. 175) and the Harness site (A.D. 220) (11). In addition,  $\delta^{13}\text{C}$  values (13, 14) show no evidence of corn consumption by Hopewellian groups. If *Cucurbita* squash was domesticated independently in eastern North America (24), then maize is the first tropical food crop to be introduced into the region. On the basis of stable carbon isotope analysis and AMS dating of early maize, corn did not precipitate either the development of Hopewellian societies or a rapid shift to agricultural economies in eastern North America (43). Rather it was adopted as a minor, almost invisible addition to well-established food-producing economies. These pre-maize economies were based on the four local domesticates discussed above, as well as on three other cultivated seed crops for which a convincing case for domestication has yet to be made: erect knotweed (*Polygonum erectum*), maygrass (*Phalaris caroliniana*), and little barley (*Hordeum pusillum*).

Early food-producing economies based on these seven local crop plants were established within a broad mid-latitude riverine zone (34° to 40° N) extending from the Appalachian wall west to the prairie margin (Fig. 1). Rather than being uniform across this broad zone, emergent food production economies exhibited variation between and within different regions in terms of the presence and relative importance of different seed crops (26, 32). Forager economies with little reliance on cultivated plants also likely persisted within some areas of this mid-latitude mosaic of emergent food-producing societies. Outside the zone, along the Atlantic and Gulf coastal plains and across the northern latitudes, forager economies based almost exclusively on wild species of animals and plants (with some *Cucurbita* cultivation) persisted until the A.D. 800 to 1100 shift to maize-centered agriculture.

The time frame of initial emergence of pre-maize food-producing economies in this mid-latitude zone was similarly variable, apparently beginning as early as 500 B.C. in parts of Kentucky and developing over a much broader region between about 250 B.C. and A.D. 200. This transition to food production economies is signaled by a dramatic increase in the representation (and assumed economic importance) of the aforementioned seven crop plants in

archeobotanical seed assemblages (Fig. 3) (3, 16). This increase is documented in mid-latitude rock shelters and caves, and in four areas where detailed, temporally long archeobotanical sequences have been established: east Tennessee (6), the American Bottom (7), central Tennessee (8), and west-central Illinois (9) (Figs. 1 and 3). More direct evidence of increasing dietary importance of these local seed crops is provided by the large sample of human paleofecal material recovered from Salts Cave (about 650 to 250 B.C.), which contained substantial numbers of marshelder, maygrass, sunflower, chenopod, and *Cucurbita* seeds. Yarnell estimates that pre-maize crop plants accounted for 75% of the plants consumed by those living at the Salts Cave site and perhaps two-thirds of all foods they consumed (27). This paleofecal evidence, along with increased representation of pre-maize crop plants in Salts Cave deposits by 500 B.C., also indicates that food-producing economies apparently developed in central Kentucky and perhaps some other areas of the East somewhat earlier than 250 B.C. (3, 27). Other indications of emerging pre-maize farming economies include the presence of chert hoes and hoe flakes, increases in pollen and macrobotanical indicators of field-clearing activities (7, 27, 44), evidence of seed storage in a variety of containers and in pit features (12), and advances in ceramic cooking vessels (45) for seed processing.

The indigenous crop plants of eastern North America had considerable economic potential, based both on available harvest yield information and on the nutritional composition of their seeds. Modern commercial production levels for sunflower, along with studies of present-day nondomesticated stands of *I. annua*, *C. berlandieri*, and *P. erectum* indicate potential harvest yield values in the range of 500 to 1000 kilograms per hectare (46). This 500 to 1000 kg/ha harvest yield projection overlaps with harvest estimates for maize in prehistoric eastern North America (400 to 1400 kg/ha) and *Chenopodium quinoa* in South America (500 to 1000 kg/ha) (46). It also compares well with historic (A.D. 1850 to 1900) mean yield values for European wheats grown during the early Neolithic: winter and spring einkorn (835, 645 kg/ha) and winter and spring emmer-spelt (1045 and 756 kg/ha, respectively) (47).

In terms of nutritional composition, pre-maize crop plants can be divided into those with starchy or oily seeds. Of the five fall maturing crops, two (erect knotweed and chenopod) have high carbohydrate content, whereas the other three are high in oil or fat (*Cucurbita*, marshelder, and sunflower). Both spring-maturing crops (little barley and maygrass) are high in carbohydrate content (16, 26).

On the basis of the most informative regional data sets available (from the American Bottom, central Tennessee, and west-central Illinois) (Fig. 1), the habitation sites of about A.D. 0 to 200 Hopewellian farming societies were small, one to three household settlements dispersed along stream and river valley corridors (16). Along segments of some river valleys having protein-rich floodplain lakes and marshes, such as the lower Illinois River, small household settlements appear to form loose spatial concentrations that have been called "villages," even in the absence of any indications of an overall community plan. Along with the seeds of crop plants, a wide variety of different species of wild animals and plants are represented in these small household settlements. Variation from household to household in the composition of faunal and floral assemblages indicate both differential species availability within individual household catchment areas and the subsistence autonomy of these basic economic units of society (48). The broad spectrum and flexible pre-maize economies of these household units also document the addition of a food production sector, with its storable harvest as a buffer against food shortage, to preexisting forager subsistence patterns, rather than the wholesale replacement of earlier, largely hunting and gathering economies.



This initial and additive emergence of multicrop food-producing economies in eastern North America at about 250 B.C. to A.D. 200, which involved seven high-yield, high-nutritional profile, spring and fall harvest crop plants represented a major economic and social transformation. Six to nine centuries later (A.D. 800 to 1100), these indigenous multicrop food-producing economies would in turn be supplemented (and even later largely supplanted) by agricultural systems centering on a single introduced tropical food crop—maize.

## The Shift to Maize-Centered Agriculture

Although introduced into at least some areas of eastern North America by A.D. 200 (11), likely from the Southwest, maize remained a minor cultigen, or perhaps a high status or ceremonial crop, until after A.D. 800. Although often labeled “Midwestern twelve row,” pre-A.D. 800 maize in eastern North America is represented by limited amounts of small kernel and cupule fragments and cannot be easily characterized or compared to either modern or proposed ancestral varieties of corn.

During the six centuries from A.D. 200 to 800, indigenous crops and food-producing economies were becoming increasingly important across the mid-latitude pre-maize farming zone (26). This gradual developmental trend took a rapid and expansive new direction between A.D. 800 and 1100, with agricultural economies based largely on corn developing from north Florida to the northern limits of maize farming. This rapid shift encompassed many of the largely forager societies of the Atlantic and Gulf coastal plains and northern latitudes as well as the mid-latitude pre-maize farming zone. This shift involved economic transitions both from long-established hunting and gathering subsistence patterns and from indigenous multicrop food production systems.

The evidence for maize agriculture across eastern North America is the marked increase in maize recovered from archeological contexts after A.D. 800 to 900 and the changing  $\delta^{13}\text{C}$  values obtained from human bone that indicate an initial substantial consumption of maize during the period from A.D. 900 to 1100 (Fig. 4).

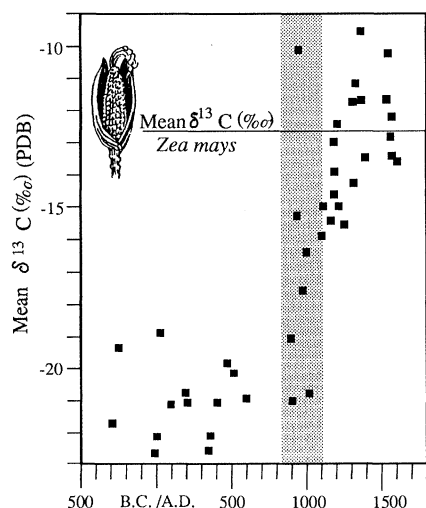
The A.D. 800 to 1100 shift to maize-centered agriculture across eastern North America was associated with the emergence of more complex sociopolitical formations. Corn played a central role in the evolution of Iroquoian societies in the Northeast and Fort Ancient polities along the middle Ohio River valley, as well as in the diverse

array of Mississippian chiefdoms that emerged along the river valleys of the Southeast and Midwest (49). These parallel but regionally distinct episodes of major social transformation have attracted a broad range of alternative explanations in which maize agriculture has been variously cast as an adaptive response to growing problems of imbalance between demographics and resources, an opportunistic effort to buffer social and economic uncertainty in the absence of external stress, and as a lever of social inequality for an emerging elite. Similarly, a number of overlapping explanations have been offered for the six-century lag that separated the initial introduction of maize into eastern North America at A.D. 200 and its post-A.D. 800 transition from minor cultigen to major crop. These explanations focus both on possible changes in how corn was used and potential changes in the plant itself. Perhaps maize was initially a controlled ceremonial crop, used by the general populace after A.D. 800. Maybe it was initially harvested and eaten in the green state and was not used as a storable food supply until after A.D. 800. Even though it may have had higher harvest rate values relative to local crops (46), maize could have remained a minor cultigen before A.D. 800 because of its larger initial investment costs in land-clearing and field maintenance. The cost-to-yield ratio of maize agriculture may have moved into a more attractive range after A.D. 800, perhaps because of increasing demographic pressure on existing wild and cultivated resources or the development of more productive varieties of maize, or both.

The development of a new eight-row variety of maize that was adapted to short growing seasons and ancestral to the historic period northern flints (50) does in fact provide at least part of the explanation for the rapid adoption of maize across the northern latitudes of eastern North America. First appearing in the Northeast, Ohio Valley, and Great Lakes by A.D. 900 to 1000, this distinctive eastern eight-row variety of maize dominated agricultural economies in those regions until European contact.

But the shift to maize-centered agriculture in eastern North America was not simply a matter of the development of new, improved varieties of corn. There is at present no evidence that any higher yield or more storable types of corn played a role in the A.D. 800 to 1100 formation of maize-centered agricultural economies and more complex sociopolitical systems in the Midwest and Southeast (26). Moreover, like the second millennium initial domestication of plants in eastern North America and the subsequent emergence of food production economies in the region at about 250 B.C. to A.D. 200 (48), the shift to maize agriculture was imbedded within a larger and uniquely eastern North American process of social transformation.

Many of the challenging new research questions to be addressed in the coming decades focus on these larger social transformational aspects of the forager to farmer transition in eastern North America and on the intricate patterns of interaction that evolved between human societies and plant populations.



**Fig. 4.** The shift to maize-centered agriculture in eastern North America, as reflected by changing mean  $\delta^{13}\text{C}$  values of human bone collagen samples from sites in the region. PDB, Pee Dee belemnite. Modified from Ambrose (14).

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# Quantifying the Information Content of Lattice Images

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Quantitative information may be extracted from local areas of images that consist of one or more types of unit cell. Fourier-space analysis, real-space intensity analysis, and real-space vector pattern recognition are discussed. The pattern recognition approach efficiently exploits the available information by representing the intensity distribution within each unit cell of the image as a multidimensional vector. Thus, the amount and the effect of noise present are determined, statistically significant features

are identified, and quantitative comparisons are made with model images. In the case of chemical lattice images, the position of a vector can be directly related to the atomic composition of the unit cell it represents, allowing quantitative chemical mapping of materials at near-atomic sensitivity and resolution. More generally, the vector approach allows the efficient and quantitative extraction of information from images, which consist of mosaics of unit cells.

A LARGE ARRAY OF TECHNIQUES, SUCH AS ELECTRON MICROSCOPY, tunneling microscopy, x-ray microscopy, light microscopy, and tomography, produce data in the form of images made up of collections of unit cells. As an example, consider Fig. 1, a (chemical) lattice image of a GaAs quantum well contained

between  $\text{Al}_{0.37}\text{Ga}_{0.63}\text{As}$  barriers. To the eye, a sophisticated but qualitative image processor, the presence of two different materials is obvious. The purpose of this article is to discuss ways in which

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